A Working Paper On

PHYSICAL OCEANOGRAPHY

OF THE NORTHWEST PASSAGE

including a research proposal for

1981 - 1984.

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This text is a working paper and is therefore subject to change from time to time as requirements change and new information becomes available. Persons interested in the present status of oceanographic research in the N.W. Passage should contact the author.

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In compiling the following notes the working paper "Transport of water through the archipelago", by H. Sandstron of B.I.O. provided a very useful guide. H. Melling of I.O.S. provided helpful comments and assistance and the theoretical argument and analysis of the measurement of seasonal variations in mean current (4.2) is taken from his working paper "Determination of water Flow in the Canadian Arctic Archipelago from Cross-channel Pressure Measurements". The discussion on numerical modelling (9.) is taken from notes prepared by F. Henry at I.O.S.

1. Introduction

This working paper first sets down the reasons why the physical oceanography of the Northwest Passage is of interest and provides a time frame for research. The important parameters are identified and subsequently developed in the following sections. Finally a proposal for research is sketched out to provide a focal point for discussion and a basis for subsequent action.

The pace of research on the physical oceanography in the Arctic Archipelago has increased over the past five or so years, largely in response to the development and shipping of mineral resources and the increasing exploration for hydrocarbons. It is now anticipated that year-round transport of hydrocarbons through the archipelago will commence by 1985 to 1986. Hydrocarbons in the form of crude oil will likely be moved eastward from the Beaufort Sea while LNG originating on Melville Island (The Arctic Pilot Project) will also be transported eastward. It is reasonable to assume that once year-round shipping through the Northwest Passage is proven feasible, global shipping interests will realise that the new route reduces the present shipping distance between Asia and Europe by 40%. One would anticipate increased shipping via the arctic route at an accelerating pace in the decades following 1985.

The geographical location of the Northwest Passage through the archipelago is fairly clear. Starting in Amundsen Gulf in the west the route is through Prince of Wales Strait, then eastward through Viscount Melville Sound and Barrow Strait. From here the route may be either further eastward through Lancaster Sound to Baffin Bay or the alternate all Canadian route southward through Prince Regent Inlet into Foxe Basin and Hudson Strait to the Labrador Sea. Place names are identified in Figure 1. The Arctic Pilot Project intends to use the Lancaster Sound - Baffin Bay route while the Prince

Figure 1. Geographical names in the Arctic Archipelago.

Regent Inlet option is under consideration by Dome Petroleum. For the purposes of this working paper, only the section from Amundsen Gulf to Prince Regent Inlet is being considered.

Both government and industry have a major interest in better understanding the oceanography of this shipping route for engineering, operational, environmental protection and regulatory reasons. The safe and efficient passage of ships and their cargoes requires understanding of ice motion, ice thickness distribution, ice edges, ocean currents and winds. Assessment of impact on the marine environment requires understanding of the physical environment. The occurrence of ice edges, leads, and polynya which are determined by current and wind affect migration of sea mammals. Currents transport nutrients, pollutants and distribute larvae. Water properties (e.g. temperature, salinity, dissolved gases and nutrients) provide a favorable or unfavorable environment for organisms and determine the density field which is fundamental to studies of ocean dynamics. Light penetration, important to photosynthetic processes depends on ice thickness and snow cover which in turn are affected by current and wind respectively. The propagation of sound emanating from ships is a function of the distribution of water density.

The above are merely examples of a complex and interrelated environment. The following specific physical features are common to one or more of the variety of subjects about which increased understanding is required.

(a) Water levels; tidal and nontidal cause of water level changes, their spatial and temporal variation.

(b) Currents; various forces superimpose to produce the spatial and temporal distribution of current found.

(c) Wind; wind stress during periods when ice is not landfast produces ice motions and surface currents.

(d) Water properties; spatial and temporal distribution of water properties are related to dynamic forces (currents). Properties identify water masses providing insight into their origins and distribution.

An understanding of physical processes is a much more efficient and useful goal than tabulating various physical features for a given period. Physical features of oceanography within the Northwest Passage are often critically dependent upon events either adjacent to or far removed from the passage itself and any scheme of field measurements should reflect this fact.

2. Background

The Arctic Archipelago is a maze of interconnecting channels joining the Canada Basin water of the Arctic Ocean in the west to the Baffin Bay and Labrador waters in the east. The general pattern of surface currents through the archipelago is summarised by Collin (1963) and is one of motion from the west or northwest to the east. While correct in the broad view, it is now known that in detail, complex currents exist with some flows to the north and east. The submarine topography of the archipelago will, at some point, limit water motion to the first 100 to 200 metres by virtue of a series of sills. Figure 2 depicts water depths as estimated from hydrographic charts. Up to three distinct bodies of water exist in the archipelago. Generally west of Barrow Sill and north of Bathurst Island Arctic Ocean water is found, while Baffin Bay water exists in Lancaster Sound and Jones Sound areas. The Alaskan Coastal Current Pacific water moves eastward along the coast of the Beaufort Sea and through the archipelago (Codispoti & Owens 1975). The fresh water input to the archipelago occurs during late spring and originates from melting sea ice and runoff from land. Walker (1977) discusses runoff volumes where estimates of average annual runoff depths vary from 2.5 to 14 cm. with the higher values in the mountainous eastern archipelago.

Sea ice cover in the Northwest Passage is variable but some generalizations can be made. Viscount Melville Sound contains land-fast ice during the late winter-spring period. The western boundary of winter landfast ice can vary from a position tangent to the western coasts of Banks and Prince Patrick Islands, to a position indenting well eastward into McClure Strait (Melling, personal communication). A shear zone marking the transition to the moving polar pack is found west of this ice edge. Marko (1978) has studied the ice edge location at the eastern portion of Parry Channel and has found

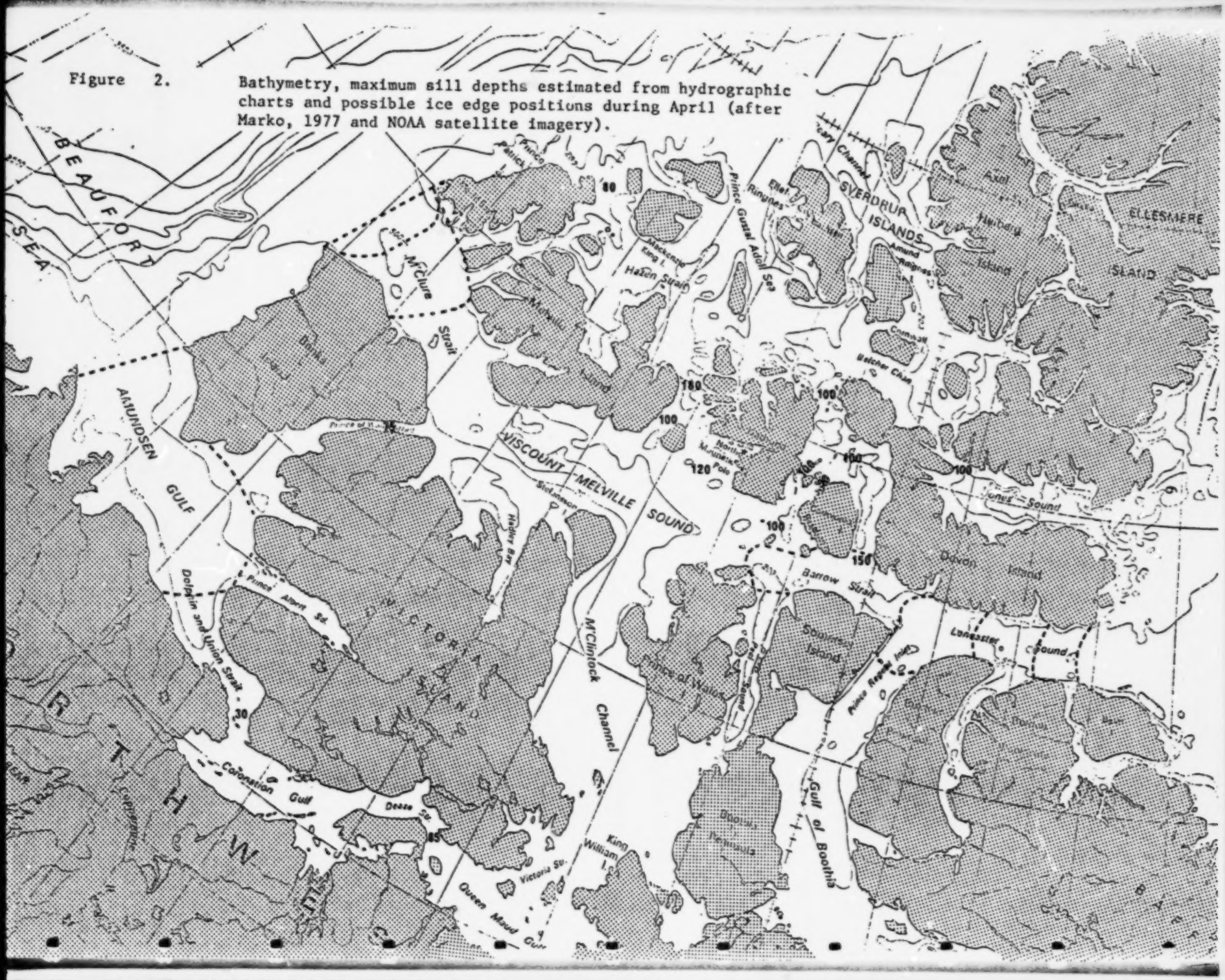


Figure 2. Bathymetry, maximum sill depths estimated from hydrographic charts and possible ice edge positions during April (after Marko, 1977 and NOAA satellite imagery).

the edge location to vary from Barrow Sill just west of Barrow Strait to the eastern end of Lancaster Sound. Intermediate locations seem to occur at preferred positions. Traditional ice edge locations are included on Figure 2. Prince of Wales Strait can normally be considered to contain landfast ice. Prince Regent Inlet and part of the Gulf of Boothia can be expected to contain unconsolidated ice when the ice edge in Parry Channel is located west of Prince Regent Inlet (Marko, op cit.). Ice edges break up in the period late June to the end of July. The period of least ice consolidation in Viscount Melville Sound occurs in late August - early September. Ice within the Sound becomes landfast again from late November to year end.

3. Water Levels

3.1 Tidal

A fair number of tidal records of varying length have been recorded in the Arctic Archipelago by the Canadian Hydrographic Service. Tidal signals are semi-diurnal (12 h period) or mixed, mainly semi-diurnal. The Atlantic tide propagates westward from Baffin Bay while the smaller amplitude Arctic Ocean tide propagates eastward. The propagation of the major tidal consitituents through Parry Channel is illustrated in Figure 2a taken from Greisman and Lake, 1978. Mean tidal ranges from east to west through Parry Channel are Dundas Harbour 1.9 m, Resolute 1.3 m, Winter Harbour 1.0 m and Sachs Harbour on the arctic coast 0.4 m.

Tides propagate through the channels of the archipelago in the form of Kelvin waves. The wave propagates forward with a boundary (coast line) on the right. The amplitude is greatest at the boundary and decays exponentially away from it. The spatial scale is given in terms of the external Rossby radius of deformation, R, where

$$R = \frac{(gh)^{\frac{1}{2}}}{f} \qquad (1)$$

where g = gravitational acceleration, 9.8 m/sec

h = water depth, e.g. 200 m

f = coriolis parameter, $2\Omega\sin\phi = 1.4 \times 10^{-4}$ rad/sec

R is in the order of 300 km. A measured tidal range at Resolute on the north side of Barrow Strait of 1.6 m would give a calculated range on the south shore of 1.3 m. The actual measured value is 1.1 m.

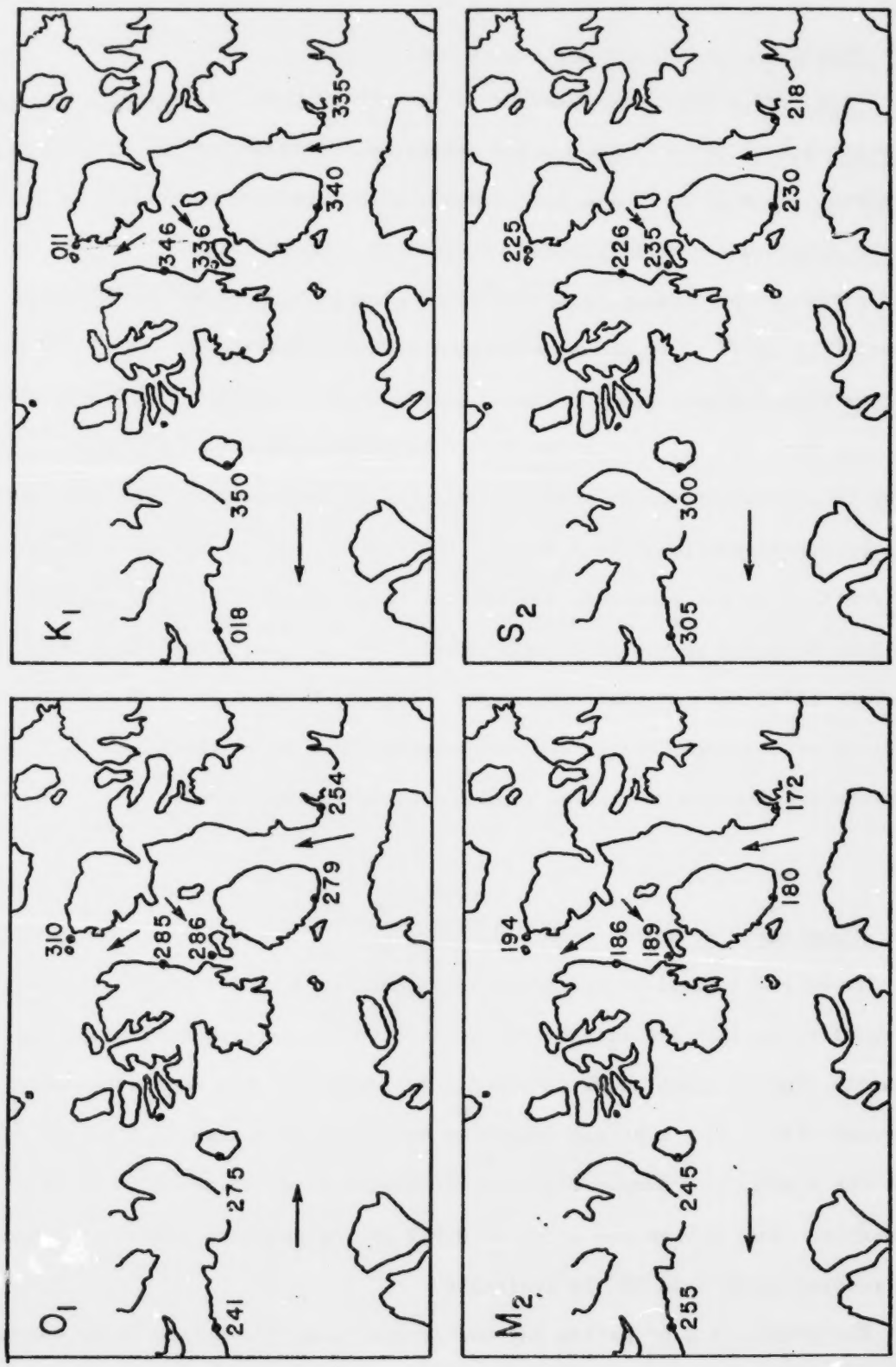


Figure 2a. Propagation of O_1, K_1, M_2 and S_2 tidal constituents.

(after Greisman and Lake, 1978)

3.2 Nontidal

Water levels will vary in response to forces other than those giving rise to astronomical tides. The dynamic balance existing during geostrophic water flow requires a slope of the sea surface, also large scale circulation patterns in the Arctic Ocean or Baffin Bay can cause periodic changes in mean water levels. Wind stress on open water will cause an increase or decrease in mean water level as water is piled up or driven off shore. Wind stress can also produce surface seiches within channels and basins. Generally frequencies of nontidal elements can span from several cycles per day to an event once in several years. If water level changes should result from inertial motions where the flow oscillates at a period proportional to latitude, the frequency of change near 75° latitude is identical to the important semidiurnal tidal constituent. In analysing the data obtained by a water level recorder one can use numerical methods to separate tidal and nontidal components. The measurement and understanding of nontidal water level changes are an important element in the study of ocean currents and discussion will be expanded in subsequent sections.

3.3 Measurement of Water Level

To record a tidal signal adequately requires a sample length sufficient to resolve the most significant tidal constituents or frequencies and the separate signals which occur as strong sidebands. It has been determined (Foreman, 1977) that a sample length of 764 hr or 31.8 days is required and that the appropriate sample interval for frequencies ≤ 0.322 c/hr is ≥ 1 sample/hr. Accuracy in the order of 0.01% of the pressure head at the gauge and resolution of 1 in 10^5 is desirable.

The propagation of Baffin Bay and Arctic Ocean tides into Parry Channel

has been reviewed. It follows that gauges located on the north shore of Viscount Melville Sound will record the strongest Baffin tidal signal while gauges on the south shore will record the strongest Arctic tidal signal.

Numerical modelling using existing tidal data can map co-tidal lines, co-range lines and amphidromic points in the basin or channel of interest. This information would provide a basis for selecting spatial scales for water level gauges (and current meters) as well as providing a framework to aid in data interpretation. A discussion of numerical modelling is given in section 9.

4. Currents

The current existing at some point in space and time can be considered to result from the superposition of two or more of the following forces:

a) tidal forces,

b) pressure gradient forces related to sea level changes,

c) gravitational forces resulting from horizontal density differences,

d) atmospheric forcing - wind stress or wind driven flows,

e) turbulent shearing or Reynold's stresses.

4.1 Tidal Currents

Tidal currents occur as the result of tidal changes in water level. Tidal currents can be filtered from a current record and the amplitude and phase of each constituent can be determined in a manner analogous to the analysis of water level data. As discussed in connection with water level data, close to 75^{o} latitude the period of the semi-diurnal M2 component is the same as the local inertial period. Rotary spectral analysis will permit separation of inertial and tidal variances. Inertial motions draw energy from transient and geostrophic flows so that the M2 current contains both tidal and inertial currents. As inertial motions are irregular the currents at this frequency would be expected to be more variable than is usual.

Tidal phases and amplitudes may differ at opposite ends of a channel setting up along channel currents in response to the resulting hydrostatic head. Applying the Bernoulli Theorem, the current speed u, can be expressed in terms of the initial speed u_o and the head, d.

$$u^2 = u_o^2 + 2gd \qquad (2)$$

Prince of Wales Strait provides an interesting example. Using an 18 day water

level record from Peel Point at the north end of the Strait and extrapolating data from Cape Parry to the south we find the result shown in Figure 3 where d, the difference in water levels, varies between 0.35 and 0.75 m. The value of u for these values of d are 2.6 and 3.8 m/sec, however, these values are unrealistic as no allowance is made for friction. An estimate of the maximum velocity when friction exists can be made. The friction stress per unit area τ is a function of water density ρ, the drag coefficient c and velocity u, i.e.

$$\tau = \rho c u^2 \tag{3}$$

For an ice covered channel of length L, width W and depth H the force due to friction is

$$F_f = \tau(2WL - 2HL) \cong 2\tau WL \tag{4}$$

where H is relatively small. The difference in water levels d at opposite ends of the channel create a pressure Δp. The driving force is

$$F_d = \Delta p HW \tag{5}$$

For frictionally limited flow

$$F_f = F_d$$

$$2\tau WL = \Delta p HW$$

substituting $\Delta p = \rho g d$ and (3) and solving for u^2 gives

$$u^2_{max} = \frac{gdH}{2CL} \tag{6}$$

If we evaluate u using values appropriate to Prince of Wales Strait, i.e. d as before, H = 75 m, L = 200 km and $C \cong 1 - 3 \times 10^{-3}$ we find the maximum velocity due to a water level difference in the presence of friction to be roughly between 50 and 100 cm/sec.

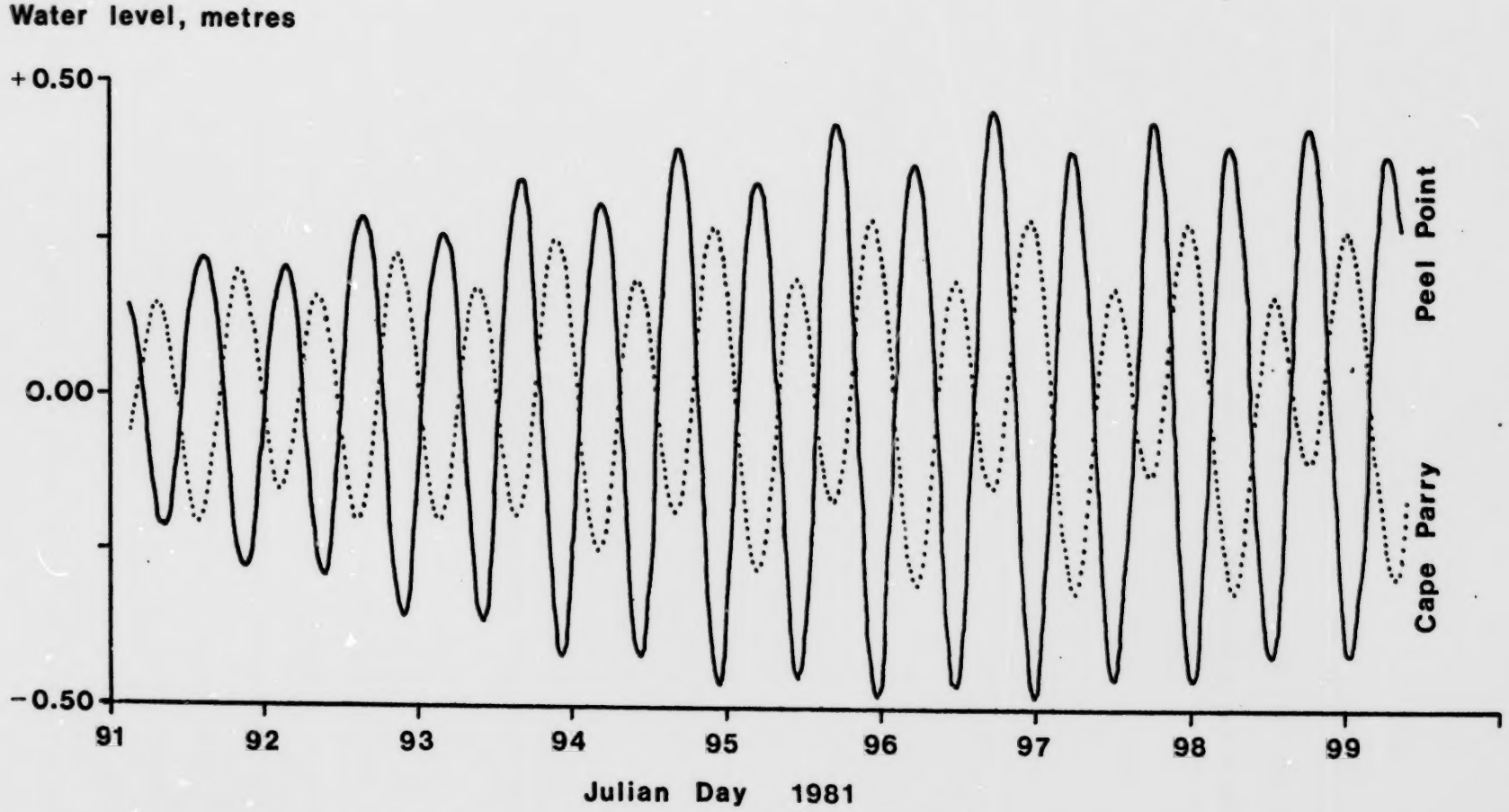


Figure 3. Water levels at opposite ends of Prince of Wales Strait based on tides at Peel Point and extrapolated from Cape Parry.

4.1.1 Vertical Variations in Tidal Flow

The magnitude and direction of tidal currents cannot be expected to be uniform with depth due to frictional stress against the channel walls and the landfast ice cover. As an illustration the following is an analysis of the M2 constituent from four vertically displaced current meters in Crozier Strait, (Greisman and Lake, op. cit.).

	amplitude of tidal elipse		
depth	major axis	minor axis	inclination
< 1 m	4.0 cm/sec	1.0 cm/sec	102°
75	7.4	-0.1	77°
200	8.4	-0.4	86°
317*	4.6	1.2	128°

* about 1 m from sea floor

Internal tide related currents which exist in a stratified water column will also contribute to variability of currents in the vertical. Such currents are the result of internal waves. An example of the vertical excursions and modes of horizontal velocity is given in Figure 4. Sills also impose vertical changes in flow patterns for they constrain flow below sill depth. Figure 5 is a current profile from inside the sill at Bridport Inlet. The sill depth is near 50 m and the bottom of the halocline is about 30 m. The surface flow is clearly stronger and the direction at 12 m is about opposite to flow at 50 m.

Greisman and Lake (op. cit.) found that the classical Ekman veering adjacent to the boundaries (e.g. the sea ice and sea floor) did not appear in measurements made in Byam and Austin Channels or in Crozier or Pullen Straits.

4.1.2 Horizontal Variations in Tidal Flow

Horizontal variations in tidal currents can occur across wider channels. The tidal Kelvin wave propagates with maximum amplitude along the right hand

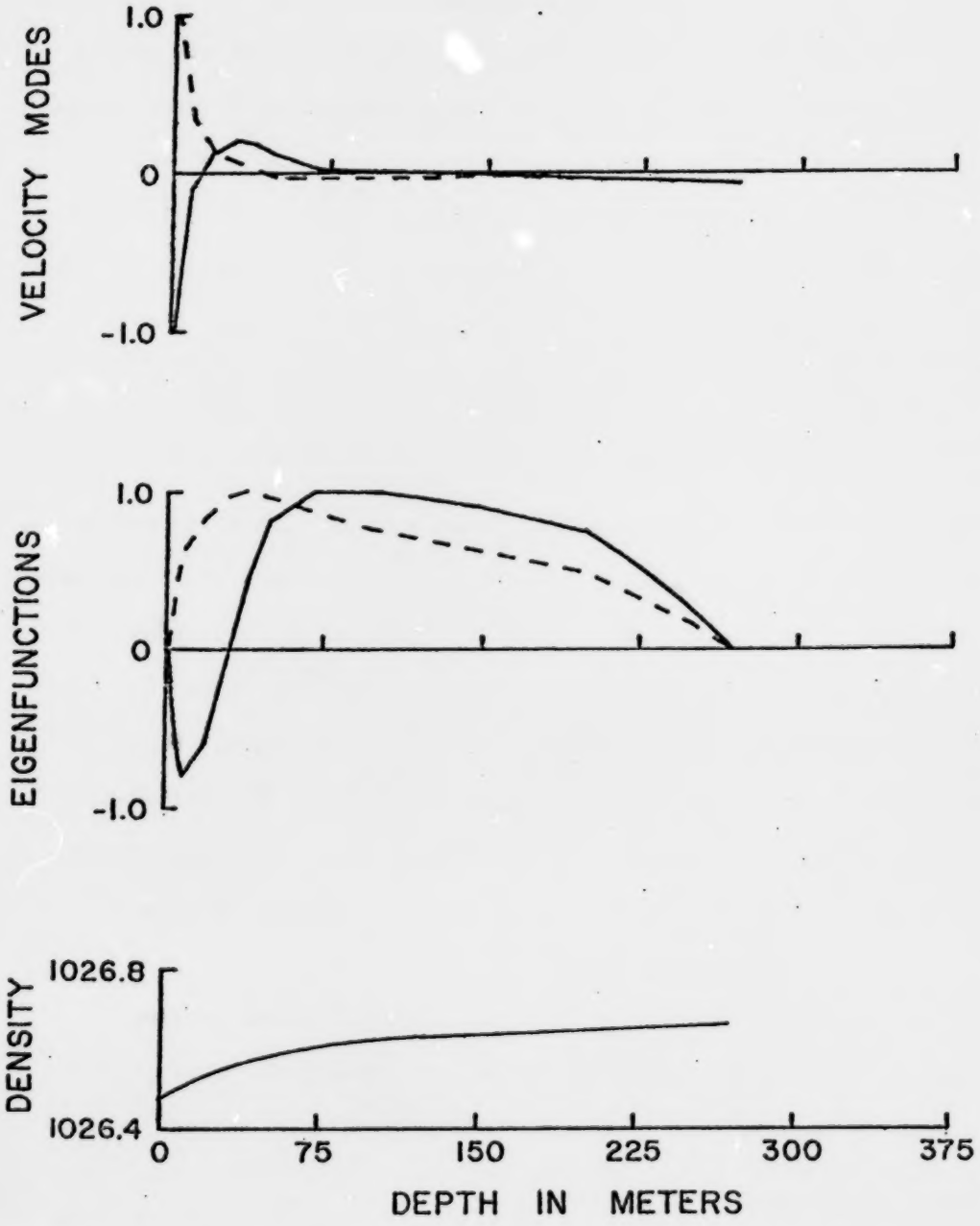


Figure 4. Particle motions resulting from internal waves for a given density profile. Eigenfunctions and velocity modes correspond to the vertical excursions and horizontal velocity respectively. After Greisman and Lake, 1978.

coast line when facing the direction of travel. As an example consider a shallow water wave propagating westward through Barrow Strait. The horizontal speed associated with the wave is

$$u = \left[\frac{g}{h}\right]^{\frac{1}{2}} a \qquad (7)$$

where h is the water depth (120 m) and a is the amplitude or half the tidal range as estimated in section 3.1. The resulting current speeds are 21 cm/sec along the north coast and 16 cm/sec along the south coast. In Viscount Melville Sound the propagation of the Baffin tide westward along the north shore and eastward along the south shore has been described. Variations in amplitude and phase of tidal current constituents across channel is expected as these two signals superimpose. Boundary effects can also result in horizontal variations in speed and direction particularly where water depth becomes shallow or headlands or spits affect the pattern of water flow.

4.1.3 Measurements of Tidal Current

Vertical variations in tidal currents require locating at least one recording current meter in the surface layer and one or more meters below this layer. In the surface layer the meter should be located below the boundary layer associated with the ice cover and above the zone of vertical shear associated with the halocline. In surface layers less than a few tens of metres thick this condition may not be realised. Below the surface layer a recording current meter would be located halfway between the halocline and the sea floor, however, if flow may be constrained by a sill, meters above and below sill depth would be appropriate.

Horizontal variations in tidal flow are on a much larger scale than variations in the vertical. Topography requires each measuring site to be

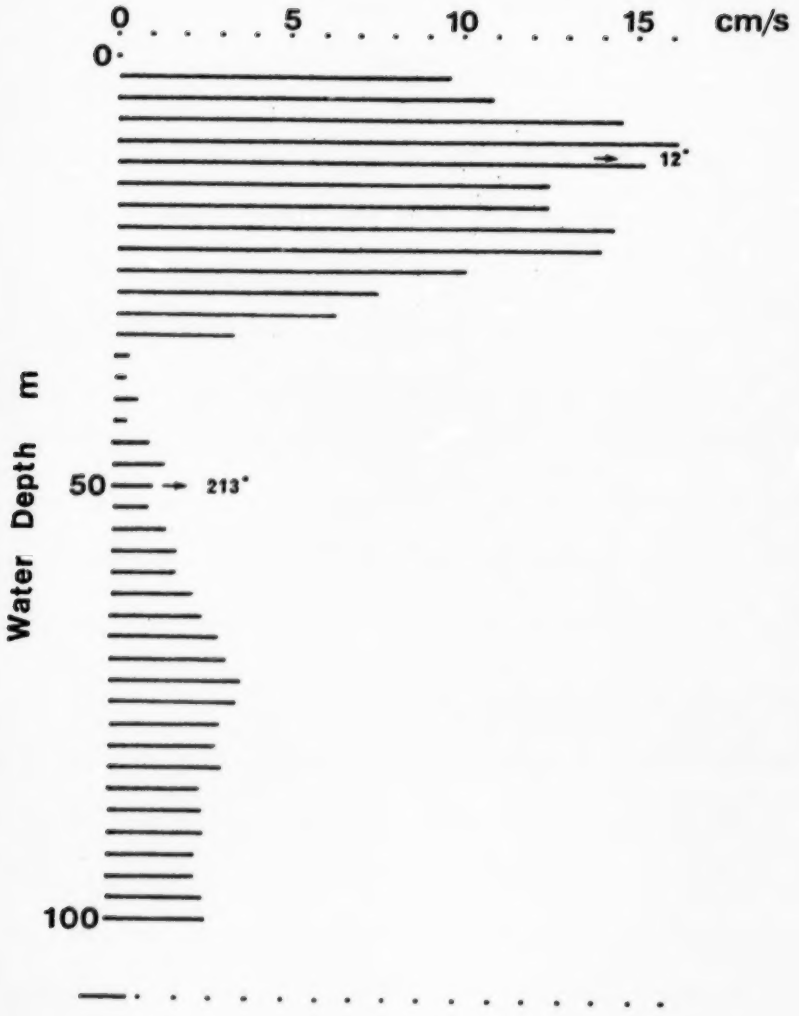


Figure 5. A profile of current speed with depth measured at the entrance to Bridport Inlet, Melville Island. Small arrows give the speed and direction of currents at 12 and 50 metre depths as measured independently by moored current meters.

evaluated individually but once away from the coast a recording current meter every 10-20 km should resolve tidal currents. Two current records from sites about 5 km apart at 100 m depth in mid-Wellington Channel showed nearly identical magnitude and orientation of tidal stream constituents.

As for tides, analysis of tidal currents requires hourly sampling of speed and direction for a minimum 31.8 day period. The analysis and prediction of tidal currents is discussed by Foreman (1978).

Recording current meters normally use Savonius rotors to detect current speed, The threshold speed required to turn the rotors is near 2.5 cm/sec. This creates a problem in data analysis particularly in wide channels like Viscount Melville Sound where currents are apt to have low velocities for significant periods of time.

4.2 Currents Due to Pressure Gradient Forces Related to Sea Level Changes

Sea level differences result in a hydrostatic head which gives rise to a current which strives to eliminate the difference. Sea level differences at opposite ends of individual channels which have their origin in differences in tidal range and phase have been discussed under tidal currents (4.1). Sea level changes also occur in response to atmospheric pressure gradients and affects of large scale circulation. Atmospheric pressure gradients occur on a scale of 100's of km but as the ocean adjusts itself isostatically at the speed of a surface wave, the sea surface would adjust itself in the order of an hour. Sea level differences due to large scale circulation of the Arctic and Atlantic Oceans appear to be sustained over periods of weeks to months. Aagaard (personal communication) has suggested a portion of the mean flow through the archipelago may be sustained by the substantial sea level difference between the North Pacific and Atlantic Oceans. Sea level changes due to Arctic Ocean circulation can be expected to affect the whole of the Archipelago.

Examples of long term variations in mean currents whose cause has not been identified have been recorded in the year-long record obtained near the sea floor in Crozier Strait, see Figure 6. Similar seasonal variations in flow from the North Atlantic have been recorded in Fram Strait between Greenland and Spitzbergen which is consistent with the idea that such long term variations are related to oceanic circulation on a global scale.

The measurement of seasonal variations in mean current requires a year-long data record. The measurement is difficult in the more active surface layer as moving ice threatens moored current meters during the summer-fall period. In principle it is possible to measure net water motion by determining the slope of the sea surface as indicated by pressure differences across channel at a particular depth. The calculation of flow from pressure differences is based on the geostrophic assumption where frictional, inertial and acceleration terms are ignored. In typical channel flow in the archipelago currents may be weak and all terms must be considered and their contributions are not easily evaluated. The following analysis is taken from an unpublished manuscript by Melling, (1980). Choosing a co-ordinate system with the x-axis (u-velocity component) along the strait and the y-axis (v-velocity component) across the strait, the equation of motion can be written:

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -fu - \frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{1}{\rho}\frac{\partial y}{\partial z} \qquad (8)$$

where f is the Coriolis parameter, ρ is the water density and τ_y is the component of frictional shearing stress in the y-direction. Integration of this equation across the strait of width L, and substituting w = 0 m/s, and at each side of the strait, v = o m/s yields,

$$\frac{\partial \bar{v}}{\partial t} + \overline{u\frac{\partial v}{\partial x}} = -f\bar{u} - \frac{1}{\rho L}\Delta p + \frac{1}{\rho}\overline{\frac{\partial \tau_y}{\partial z}} \qquad (9)$$

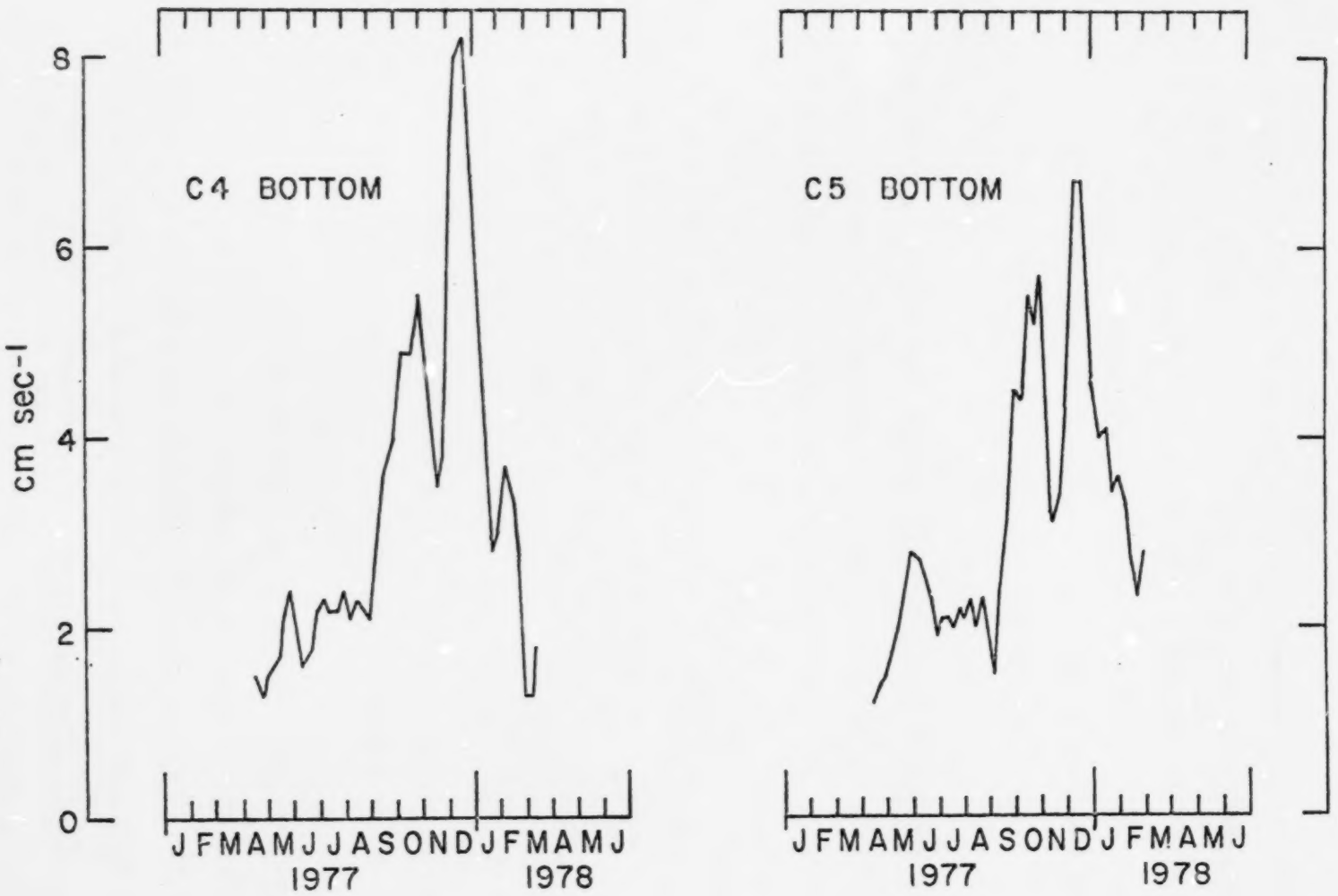


Figure 6. Seasonal variation of mean current speed at two locations in Crozier Strait. Values averaged over successive seven day periods (after Greisman and Lake, 1978).

This equation utilises parameter values at the depth of pressure measurement for any cross-section of the strait, where Δp is the pressure difference across the strait at that depth. Expressing the inertial term as: $u \frac{\partial v}{\partial x} = \frac{u}{R} + v \frac{\partial u}{\partial x}$ in order to illustrate its dependence on the radius of curvature of the flow, R, and on the streamwise acceleration gives:

$$\Delta p = -\rho L f \bar{u} + L \overline{\frac{\partial \tau_y}{\partial z}} - \rho L \overline{\frac{\partial v}{\partial t}} - \rho L \overline{\frac{u^2}{R}} - \rho L v \overline{\frac{\partial u}{\partial x}} \quad . \tag{10}$$

The relative importance of each term on the right-hand side of the equation in determining Δp can be estimated for a "typical" Arctic channel. Note that the equation $\Delta p \equiv - L f \bar{u}$, represents true geostrophic flow. Relevant parameter values are:

$\rho = 1025 \text{ kgm}^{-3}$

$L = 50 \times 10^3 \text{ m}$

$f = 1.4 \times 10^{-4} \text{ s}^{-1}$

$\bar{u} = 0.1 \text{ ms}^{-1}$ (tidal) $\qquad \bar{u} = 0.1 \text{ ms}^{-1}$ (long term)

$\overline{\frac{\partial \tau_y}{\partial z}} = 0.005 \text{ Nm}^{-2}$ in surface and bottom Ekman Layers

$\overline{\frac{\partial \tau_y}{\partial z}} = 0 \text{ Nm}^{-2}$ within body of flow

$\overline{\frac{\partial v}{\partial t}} = 5.8 \times 10^{-6} \text{ ms}^{-2}$ (tidal) $\qquad \frac{\partial \bar{v}}{\partial t} = ?$ (long term)

$R = 100 \times 10^3 \text{ m}$

$v = 0.04 \text{ ms}^{-1}$ (tidal) $\qquad v = 0.02 \text{ ms}^{-1}$ (long term) ?

$\frac{\partial u}{\partial x} = 2 \times 10^{-6} \text{ s}^{-1}$

The terms contributing to Δp, from left to right, are due to Coriolis effect, to friction, to time variation, to centrifugal "force" and to advective acceleration. The magnitudes of these terms for the parameters above are as

follows (in millibars) :

	Tidal Flow	Residual Flow
Coriolis	7.18	7.18
Friction	2.50 (0)	2.50 (0)
Time Variation	2.97	<2 ? *
Centrifugal	0.05	0.05 ǂ
Advection	0.04	0.04 ǂ

* Knowledge of mesoscale flow variability is very limited.

ǂ These terms do not decrease appreciably when time averaging is introduced. Moreover, since they are quadratic in flow speed they grow rapidly with increasing current.

The most important "correction" terms are clearly due to friction and to time variation. Frictional corrections are confined to the surface and bottom boundary layers (thickness 10 - 30 m). In these layers they may contribute about 30% of Δp, but they are difficult to evaluate even in winter when both the ice cover and the sea floor exert a passive drag. In summer, wind driving at the surface further complicates the correction. In shallow water ($\lesssim$ 50 m) frictional corrections will be important at all depths. In deeper water a layer feeling negligible frictional influence is present and no correction need be made therein. Time variation in the cross-strait component of flow is difficult to correct for without the direct current measurements which one is trying to avoid. While prior tidal surveys may suffice to compute corrections at tidal frequencies, the limited understanding and stochastic variability of lower frequency fluctuations prevent accurate correction in this range.

The use of cross channel pressure measurements may not provide a quantitative measure of net transport that could be quoted with good confidence. The measurement of long term variations in net transport may, however, prove

useful.

Water level gauges used to measure pressure differences as described above or long term current meter moorings will of course be measuring an effect rather than the cause of long term changes. To gain an understanding water levels should be monitored continuously at sites within and adjacent to the archipelago. The most important sites are along the northwest coast of the archipelago adjacent to the Arctic Ocean and in Baffin Bay. Such measurements would provide information on seasonal variations of water level with respect to the local mean water level.

Understanding of the causes of variation in circulation of the Arctic Ocean will require oceanographic studies in the Arctic Ocean and ultimately even further abroad.

Seasonal variations in water flow cannot be attributed entirely to gradient forces related to sea level changes and it will be necessary to investigate other causes. Variations can also result from long term changes in gravitational forces resulting from horizontal density differences and for shorter periods during the summer from wind stress. Currents attributable to these forces are discussed in subsequent sections.

4.2.1 Measurement of Currents Due to Pressure Gradient Forces

The minimum useful period over which information on seasonal changes in mean flow can be recorded is one year. Current meters and water level gauges would need to record data at intervals of an hour or less in order that data not be aliased by signals at tidal frequencies.

Moored recording meters will record the longer period variations in flow but can be located in the more active surface for only 4 or 5 months of the year. At a particular site a meter would ideally be located in the surface layer with one or more meters deployed below this layer using criteria

discussed under the measurement of tidal currents. Horizontal spacing of current meter arrays should be sufficient to sample distinct flows within a channel. For example, separated flow is known to occur in Wellington Channel with northward flow along the east side and southward flow along the opposite side of the channel and a minimum of one array in each flow is required. To determine most useful positions for arrays requires some prior knowledge of large scale flow features as might be determined by a CTD survey of water structure (see 5).

The use of water level gauges located on opposite sides of a channel as a means of measuring net transport in the surface layer has been discussed above from the theoretical point of view. The water level gauges themselves do not preclude using this method. Gauges presently available have an accuracy and resolution of 0.01 % and 0.001% of full scale range respectively. For a full scale range of 30 db (30 m water depth) accuracy and resolution are 3 mm and 0.3 mm. Calibration drift, which may vary by 0.05% over a year, even for an artifically-aged transducer, reduces the accuracy, in the case of our example, by up to 15 mm. The measurement of net transport requires leveling of gauges with respect to each other to an accuracy of $\leq$ 1 cm. Conventional leveling techniques with first order vertical control would provide an accuracy of 1.25 cm in 10 km but it is unlikely this order of accuracy could be obtained under arctic conditions. Hydrostatic leveling requires a liquid filled tube connecting the two gauging sites. This method is capable of providing sufficient accuracy but over long distances becomes expensive and cumbersome. An estimate of the difference in gauge levels could be obtained by evaluating the terms on the RHS of equation 10. During the spring ice-covered period, current meters spaced at appropriate intervals across the channel would provide a basis for evaluating the Coriolis and time variation

terms of the equation. The friction term could be evaluated by taking current profiles beneath the sea ice cover. Considering the accuracy of the evaluation, centrifugal and advection terms in the equation might be assumed equal to zero. An estimate of Δp could be made after which the current meters are no longer needed for this purpose and could be removed. For wide channels ($\geq$ 20 km) the number of current meters required may pose a practical problem. In summary it may be possible to obtain only rough estimates of net transport in the surface layers ($z \leq 30$ m) on a year round basis as well as obtaining a record of variations in mean flow with time, particularly in narrow channels with strong flows.

Doppler and doppler correlation current meters presently under development show some promise in avoiding the existing problems in measuring currents, particularly in the surface zone. The principle of operation involves transmitting an acoustic pulse and the analysis of the doppler shifted return signal from moving reflectors (silt, ice, biological material, etc). In theory such an instrument could be located safely on the sea floor and, by using a gating technique, determine the mean current in discrete layers from the sea floor to the surface and would, in addition, determine sea ice motion. To be of use by 1982 or 1983 an additional effort would be required to accelerate the present program of electronic packaging, software development and testing.

4.3 Currents Due to Gravity Forces Resulting from Horizontal Density Differences.

Where adjacent water masses having dissimilar densities exist gravitational forces cause the lighter water to overflow the more dense water. The water will move as described by the equations of motion and (ideally) reach equilibrium such that the coriolis force is balanced by the horizontal pressure gradient i.e. a geostrophic current exists. If one makes some assumptions

(e.g. no friction) it is possible to estimate the geostrophic component of flow by determining the horizontal distribution of density in the water column. LeBlond (1980) has applied geostrophic dynamics to account for many of the features of surface flow through the archipelago. Geostrophic flow under the influence of the coriolis force will tend to be bounded by the coast on the right side looking downstream. As long as the radius of curvature, r, of the coast is large enough (i.e. Rossby No., $u/fr \ll 1$) the geostrophic flow can turn corners without separating from the coast. Since f, the Coriolis parameter, increases with latitude this condition is most easily met at high latitudes. The geostrophic flow thins out in the cross channel direction so that, if the channel is wide enough, the interface between the upper layer of geostrophic flow and the lower layer intercepts the free surface and the current is limited to a wedge on the right hand side of the channel. Given a channel of sufficient width there is room for two geostrophically balanced upper layer flows to proceed in opposite directions on the opposite sides of the channel. An example is found in Wellington Channel. The distribution of measured density and water velocity is shown in Figures 7 and 8 respectively.

If a horizontal pressure gradient change is superimposed on a steady state frictionless flow in geostrophic balance a fluctuating component of velocity will occur. It can be shown that the period of this fluctuation is $2\pi/f$ where f is the coriolis parameter i.e. the Inertial Period and the fluctuating velocity rotates in a clockwise direction. The oscillations decay due to friction; however, when the flow exists in the very stable surface layer often found in the Arctic, there is little momentum transfer downward and the flow can persist for long periods.

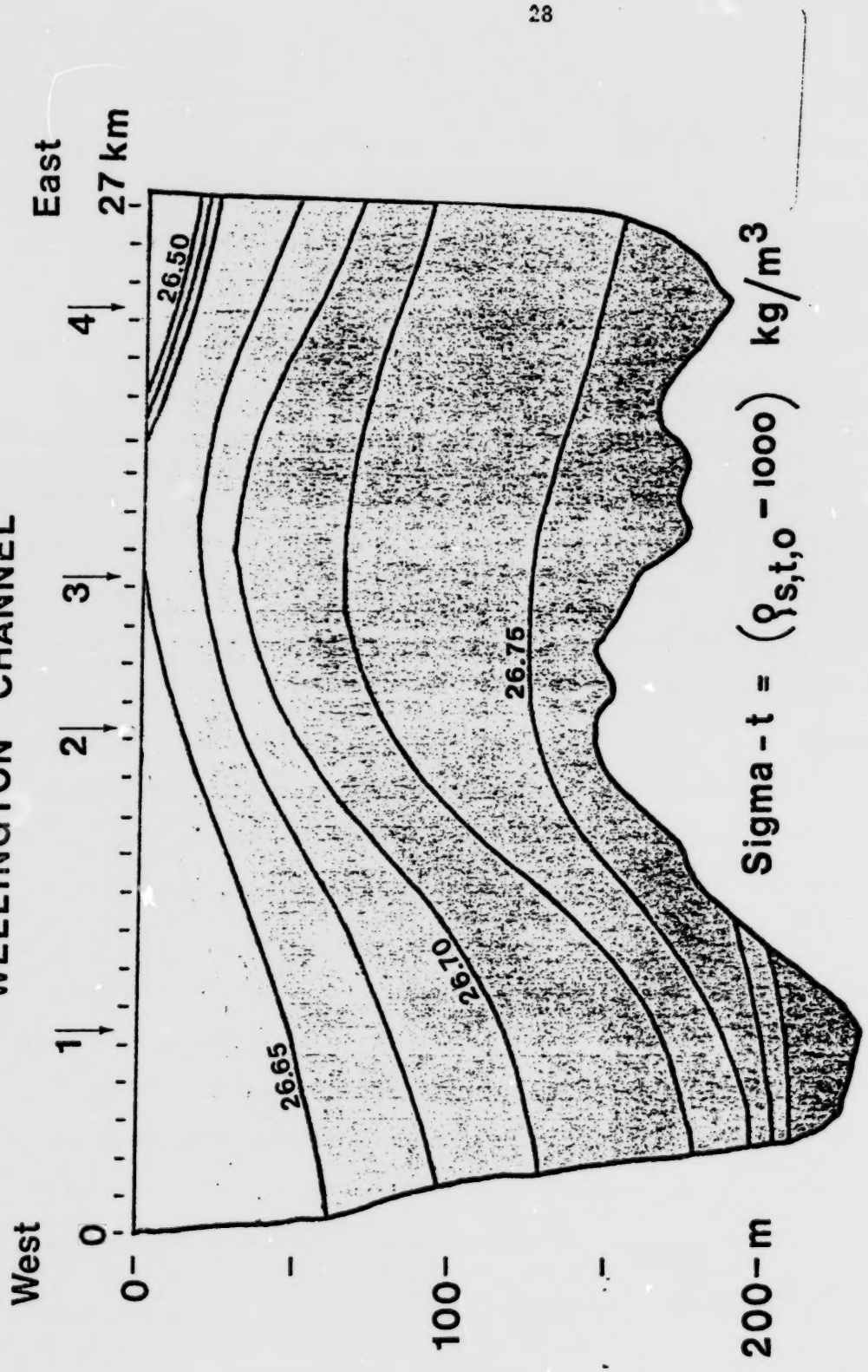


Figure 7. Distribution of density across Wellington Channel estimated from measurements obtained at four sites.

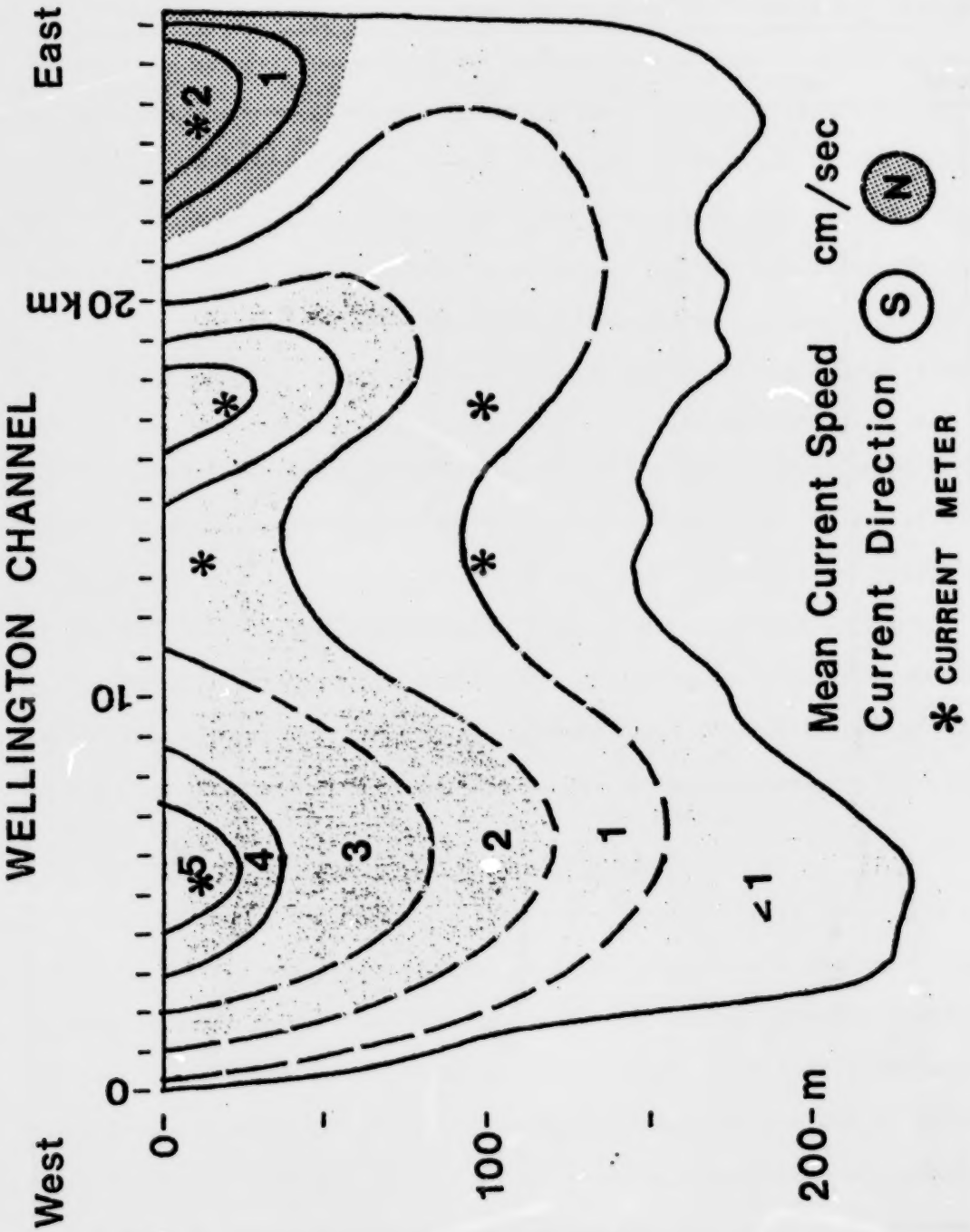


Figure 8. Distribution of mean current across Wellington Channel estimated from current meter measurements.

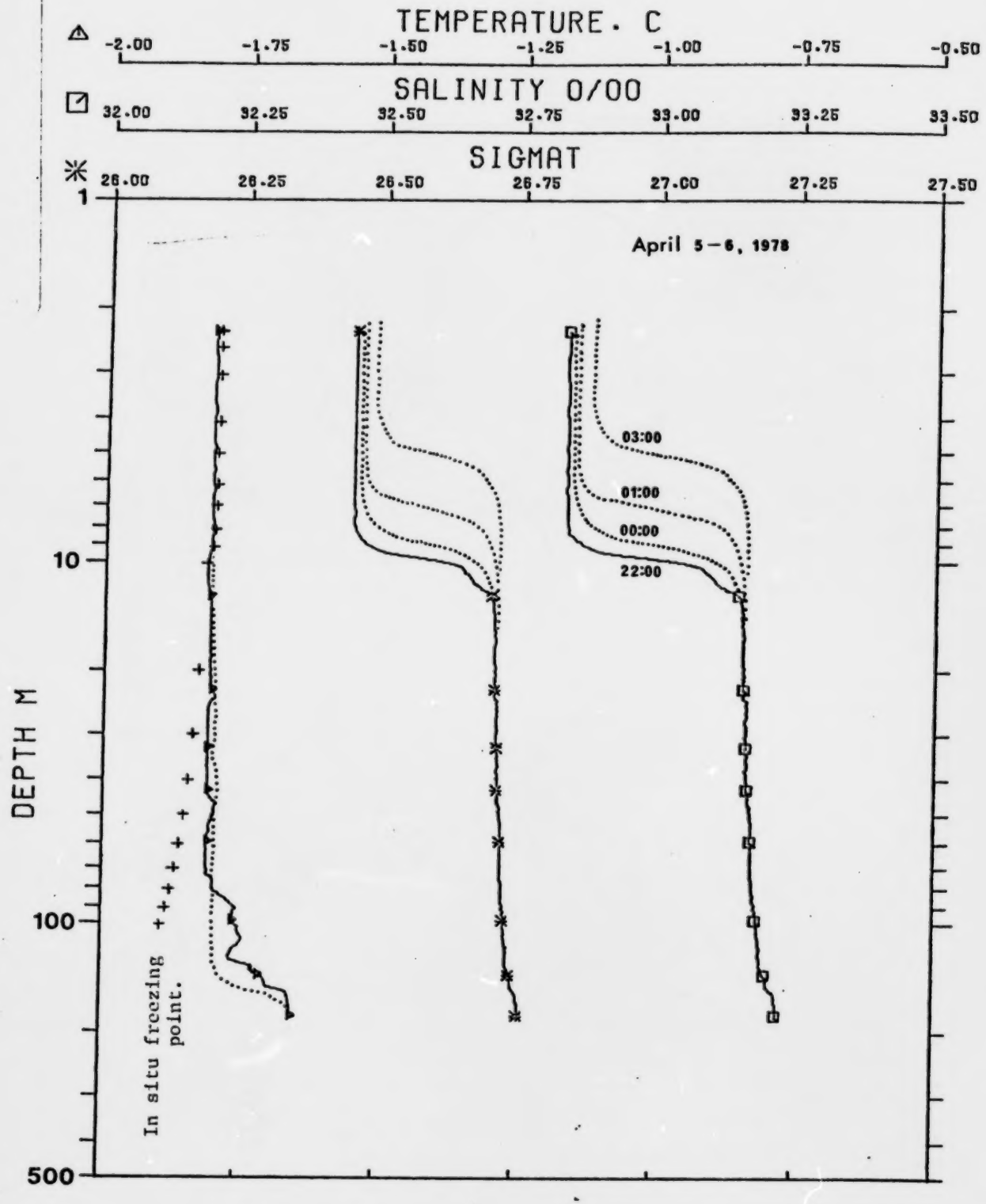


Figure 9. Short term variations in salinity and temperature profiles attributed to tides. Data are selected from 25 sequential hourly measurements in Wellington Channel, see site 4, Fig. 7.

4.3.1 Measurement of Geostrophic Currents.

Following LeBlond (op. cit.) an estimate of the lower limit for the width of the coastal geostrophic current for typical distributions of density in the archipelago gives values as narrow as a few kilometres only. In determining the spatial distribution of density as measured by CTD profiles the size of geostrophic features will have to be taken into account. This normally requires a degree of real-time output from the profiling CTD instrument so the operator can adjust spatial resolution as required.

The geostrophic flow calculated from knowledge of the density field will include some part of the tidal current (see 4.1). Figure 9 illustrates the cycling of the halocline depth in response to the tide. To document periodic changes in density structure requires obtaining data from a series of CTD profiles over a tidal cycle or better still obtaining longer term records from CT chains. The current itself can be measured directly with a properly positioned moored recording current meter but again problems arise as the geostrophic flow is contained in the surface layer which holds the threat of moving ice. Previous remarks on data sample rates discussed in 4.2.1 apply.

4.4 Currents and Ice Motion Due to Wind Stress.

During the period where sea ice is moving or entirely absent the wind stress can have a significant affect on water motions in a variety of ways. In Parry Channel this period is roughly June to October although open water can occur from Barrow Strait eastward at any time. Wind driven currents change water levels along coast lines where compensating flows are set in motion which can affect both surface and deeper layers. It has been estimated that a 10 m/sec (22 mph) wind blowing along Parry Channel would produce surface currents in the order of 15 cm/sec and sea level differences across channel near 20 cm. Storms passing over areas of large fetches such as the Beaufort

Sea can produce very significant water level changes or storm surges. In a review of monthly mean water levels in the Canadian Arctic, Walker (1971) found evidence for storm surges in water level data was confined to the Beaufort Sea zone. This limitation reflects the limited fetches available within the archipelago. In a study of storm surges in the Beaufort Sea, Henry and Heaps (1976) found surges in the form of both increasing and decreasing water levels with amplitudes in the order of 1 m. While surges normally occur during the period July - November, surges were occasionally found during winter months. In areas adjacent to the Beaufort Sea surges can produce dissimilar water levels at opposite ends of a channel giving rise to currents similar to those caused by tides of dissimilar range and phase previously discussed (4.1.2)

Relaxation oscillations may take place after the wind stress decreases in bounded bodies of water like the channels of the Archipelago. These are standing waves or seiches that will continue until the mechanical energy associated with the motion is dissipated. Also when wind passing over the water surface drops off the surface currents set in motion by the wind continue to flow under their own momentum until friction dissipates the available energy. Inertial flow is established where the coriolis and centripetal forces are in balance and circular flow occurs in the clockwise sense (in the northern hemisphere) with a radius of curvature proportional to water velocity and inversely proportional to the coriolis parameter. At 75^{o} latitude an inertial current of 20 cm/sec would move in a circle of radius near 1.5 km. As previously mentioned, inertial motions in the thin, stable Arctic surface layer persist for long periods as little downward momentum transfer occurs.

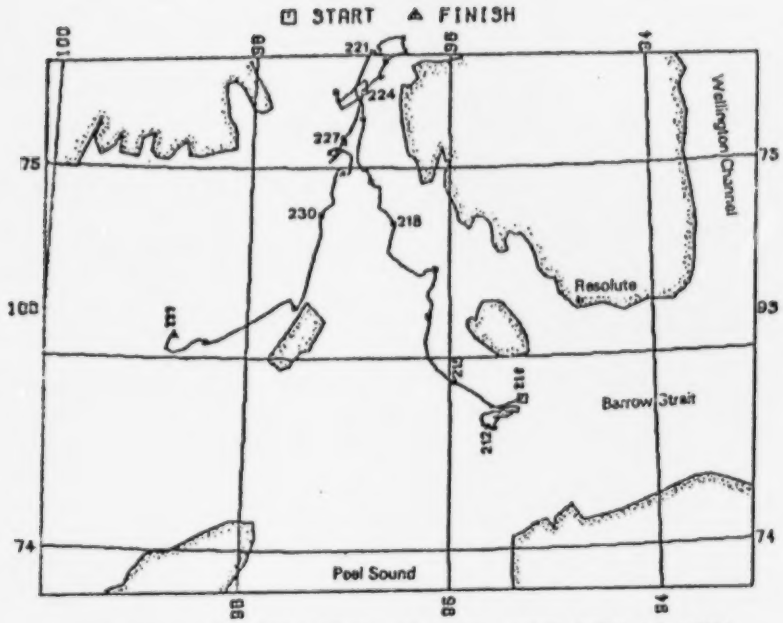
Wind stress is of great importance in the breakup, transport and convergence of sea ice which are vital to the operation of ships and several aspects of environmental protection.

4.4.1 Measurement of Currents and Ice Motion Due to Wind Stress.

In unconfined waters wind driven currents occur on a synoptic scale while along coastlines long shore currents and upwelling can occur with a spatial scale of 1 - 10 km. Mesoscale winds in the order of a few kilometres and periods of hours can have important local effects e.g. drainage winds down a river valley.

Recording barometers and atmospheric pressure data from the AES station at Resolute permitted Hill et al (1978) to produce a good correlation between calculated geostrophic winds and winds measured at two stations in Barrow Strait. Fissel et al (1978) carried out a study of satellite tracked drift buoys in conjunction with this study. The authors found a null correlation between measured surface wind and buoy drift, however, this results was in part attributed to the limited coincidence of the buoy to a nearby wind recording site during periods of significant winds. In addition the drogued buoy configuration caused the buoy to respond to motions beneath and partially decoupled from the fresher surface layer.

Anemometers situated on the coast are often affected by local topography and do not always represent conditions in the middle of a channel. This particularly applies to wider channels such as Viscount Melville Sound. Geostrophic wind calculated from the atmospheric pressure field may provide more realistic data for use in correlation of wind with large scale water and ice



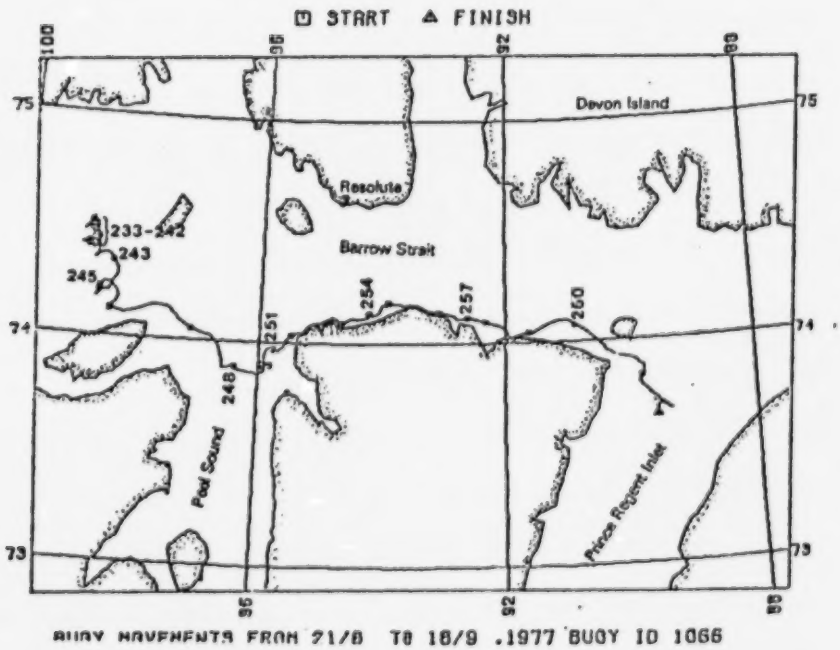


Figure 10. The smoothed track of satellite tracked drift buoys, (after Fissel and Marko, 1978).

motion. To determine the pressure field recording barometers spaced at intervals of 100-150 km around the channel of interest would be required to augment AES data.

Surface currents during periods of ice motion are best measured by means of Langrangian tracers such as moving ice floes or trackable drift buoys, as moored current meters have little chance of survival. Results of a study using drift buoys in eastern Parry Channel are given in a report by Fissel et al (op. cit.) and this technique was again used in 1980. A typical buoy track is reproduced in Figure 10. Radar tracking of ice floes was undertaken at the north end of Byam Martin Island in 1976 and at the east end of Griffith Island off Resolute in 1977, (MacNeill et al, 1978). In the later study the program was coordinated with the satellite tracked buoy program. Comparison of drogued satellite buoys to ice floe movement showed their average movements to be quite similar although periodically the ice floes and buoys moved quite differently. This emphasises an important difference between the two Lagrangian tracers. Buoys by design respond to ocean currents with minimum direct exposure to wind stress. Ice floes are susceptible to direct wind stress and form drag which is complicated by the infinite variety of floe shapes, surface roughness, size and orientation.

Radar provides a means of tracking individual ice floes for a few hours within a limited area, say a 12 mile radius. Landsat satellite imagery has a useful resolution of a few 100 m and has wide spatial coverage (185 X 185 km) but data recovery is limited by cloud cover and the frequency of satellite overpasses. At 75^{o} latitude a given point is included once a day for five consecutive days in every 18 for each satellite. Such limited temporal resolution permits documenting only large scale motions. Technically aerial photography can provide useful data with reasonable spatial and temporal

resolution; however, this technique requires large numbers of flying hours and cooperative weather.

HF radar as an ocean remote sensing tool has recently been developed by the Wave Propagation Laboratory of N.O.A.A. From a portable shore station it is possible to map sea surface currents and wave conditions over an area extending out some 60 km with an aerial resolution of a 2.5 X 2.5 km. Such a system uses the radar reflections from waves and ice floes. An HF Doppler transponder system could be used to produce instantaneous velocity vectors of the target (i.e. a transponder) which could be located on an ice floe or on a surface drift buoy, (Evans, 1981). It is possible to track hundreds of low cost ($\sim$ \$400) transponders sequentially to ranges as great as 150 km. It is unlikely that such a system would be commerically available before summer 1981 and would be moderately expensive (\$90,000 for a shore station). C-Core in Newfoundland may undertake an evaluation of HF radar techniques.

5. Currents Due to Turbulent Shear Stresses

When water flow becomes turbulent the non-linear terms give rise to terms in the equations of motion that are akin to friction and result in a more rapid distribution of momentum. These "Reynold stresses" can convert energy from the oscillatory or tidal flow to the mean flow and, as an example, can be responsible for the residual circulation within Bridport Inlet on Melville Island, Lake (1979). This component of mean flow resulting from Reynold stresses may generally be considered negligibly small but may become significant in narrow passages such as Bellot Strait.

6. Water Properties

The importance of mass distribution as determined from measurement of temperature (T) and salinity (S) has already been discussed in connection with geostrophic currents. Temperature and salinity together with certain chemical constituents can serve to label a parcel of water so that with appropriate measurements it is possible to identify the origin or source of a body of water under consideration. In Parry Channel for example, it is of interest whether water originated in the Arctic Ocean or Baffin Bay. Expected variations in TS profiles as presented by Walker (1977) are reproduced here as Figure 11. The water in Lancaster Sound below 300 m or so is colder and less saline than water at the same depth west of Barrow Strait and neither water mass can be derived directly from the other profile by vertical motion. Figure 12 presents the same information in a conventional TS diagram. The TS signature of water masses clearly differ between M'Clure Strait and Lancaster Sound. In this figure the dates as well as location are given and an important point is brought forward, the figure includes differences in water properties that may reflect seasonal and longer term differences. In a paper by Lazier (1980) significant seasonal and long term (i.e. 10 year) variations in water properties in the Labrador Sea are discussed. The monthly average of salinity at eleven depths is reproduced from Lazier's paper as Figure 13. The frequency with which water masses having different properties come in contact and interact dynamically can vary from seasonally to once in several years.

In addition to temperature and salinity chemical constituents of sea water also serve as useful tracers. Most of the Bering Strait inflow to the Arctic Ocean is thought to leave the Arctic via the Canadian Archipelago (Codispoti and Lowman, 1973). Pacific water travelling northwards through Bering Strait has a strong reactive silicate and reactive phosphorus signal. Codispoti

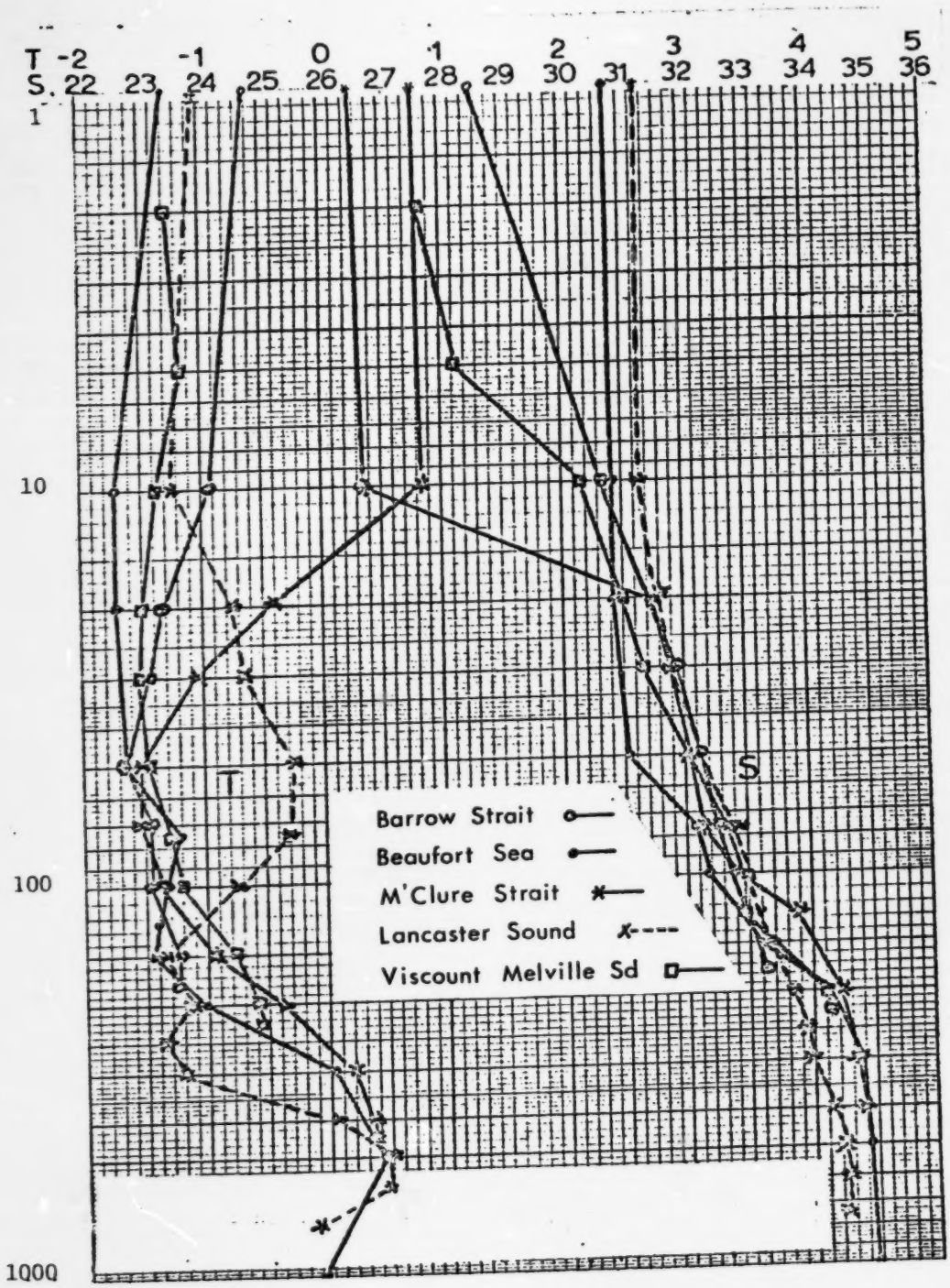


Figure 11. Temperature and salinity profiles through Parry Channel, (after Walker, 1977).

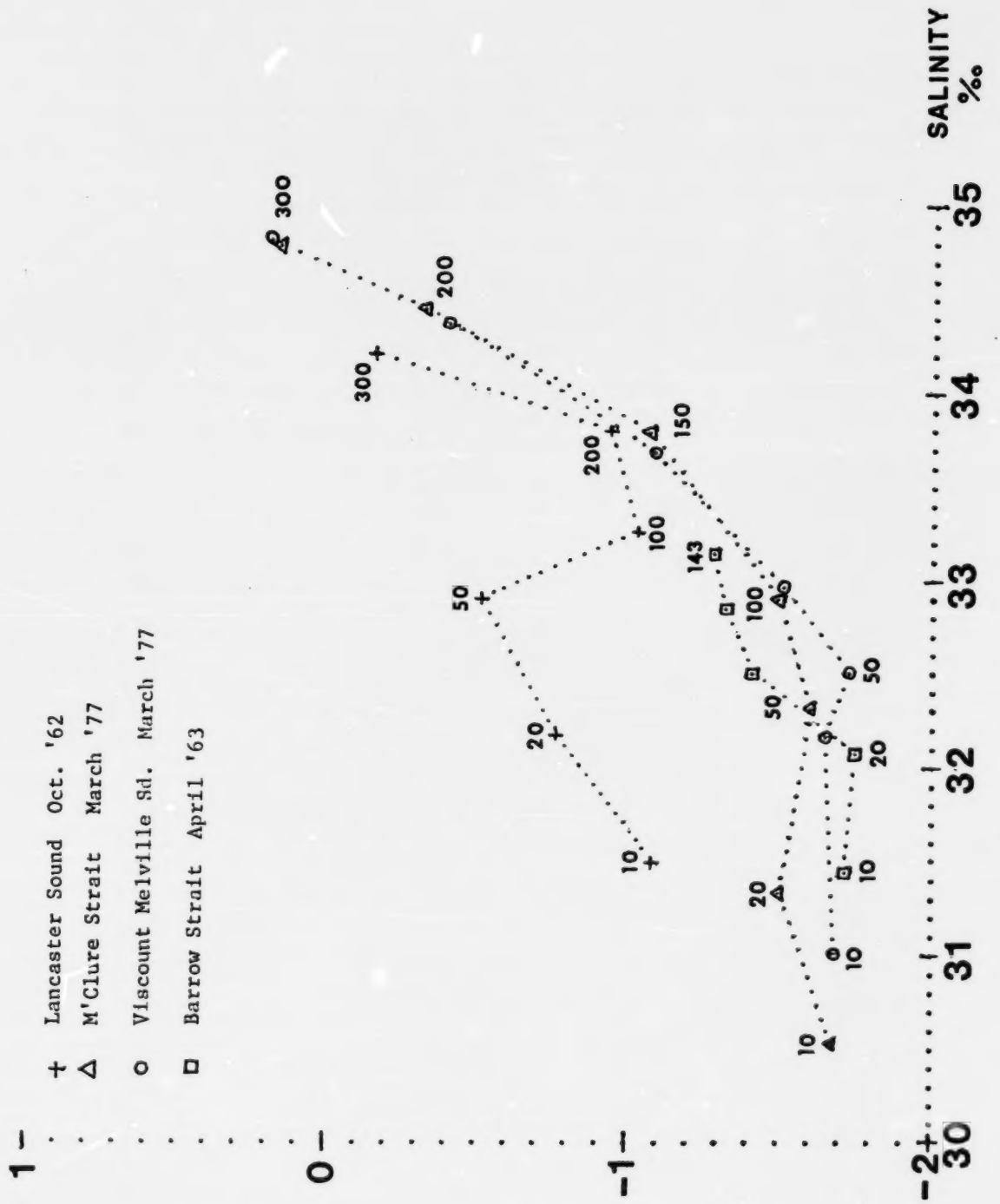


Figure 12. TS diagram for four sites in Parry Channel. 1962-63 data from BIO cruise, 1977 from CCIW data.

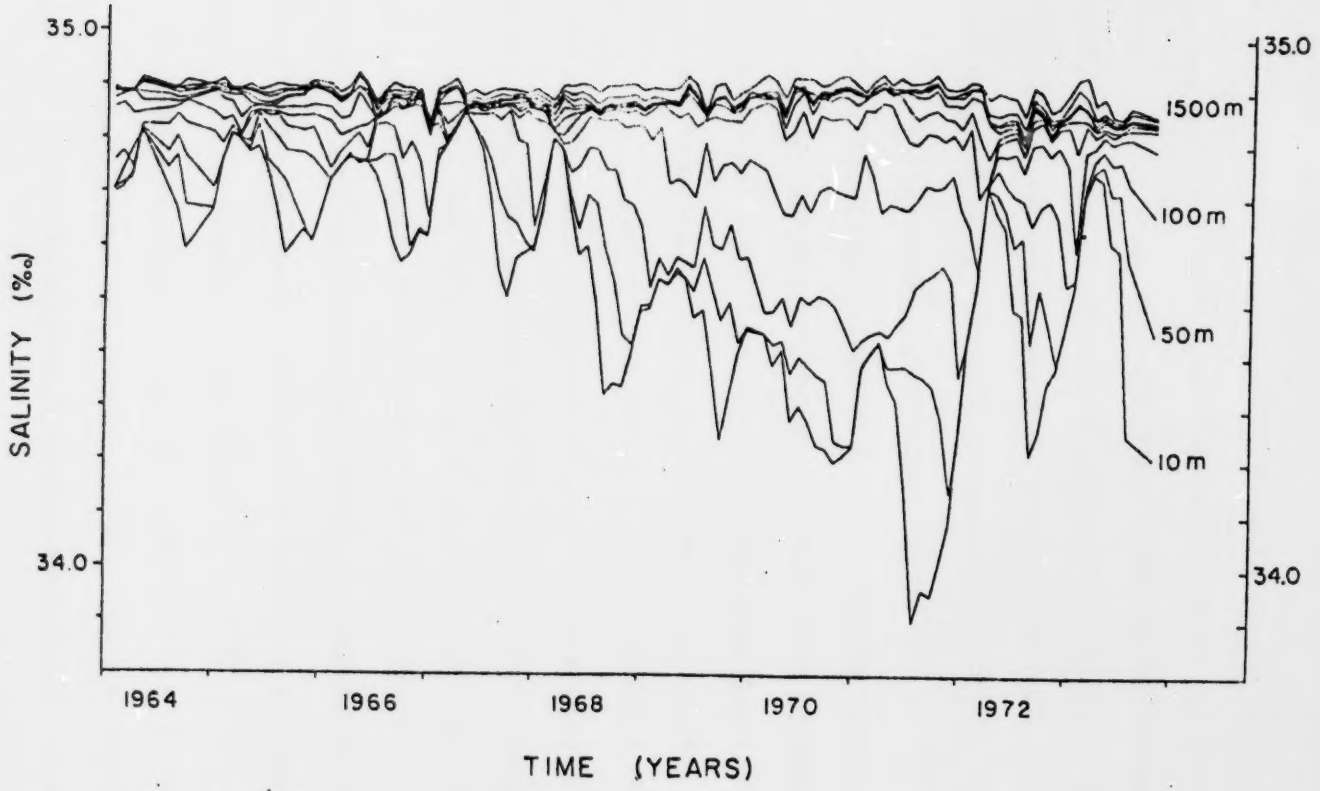


Figure 13. Monthly averages of salinity at eleven depths at Station Bravo from 1964-1973, (after Lazier, 1980).

and Owens (1975) concluded that Lancaster Sound is enriched with Bering Strait waters.

6.1 Measurement of Water Properties

In addition to obtaining TS profiles within a prescribed study area (see 4.3) it is important to identify water properties in key adjacent areas. These areas are Amundsen Gulf, western M'Clure Strait, Sverdrup Basin, Lancaster Sound, Gulf of Boothia and southern M'Clintock Channel. A body of water under study in Parry channel can be a remnant of water previously located elsewhere (e.g. Amundsen Gulf, Lancaster Sound) but subsequently replaced by water of different properties. For this reason, TS profiles routinely collected every month or two in key areas would be an aid in interpreting data. However, the practical problems of such a scheme are obvious.

To be of practical use, TS (or CTD) profiles should consist of vertical measurements at metre intervals with increased spacing at large depths. Temperature measurements should be accurate to $0.005^{o}C$ and have a precision of $0.002^{o}C$; salinity should have corresponding values of 0.01 $^{o}/oo$ and 0.005 $^{o}/oo$. CTD profiles should be taken in the manner described by Lewis and Sudar (1972) and Fofonoff et al (1974) while salinity should be computed from the Practical Salinity Scale, 1978, (Perkin and Lewis, 1980).

Long term monitoring of TS profiles might be obtainable from moored TS chains (Lewis and Sudar, 1978), however the longer term stability of such chains in the field has yet to be demonstrated.

7. Practical Problems of Current Measurement

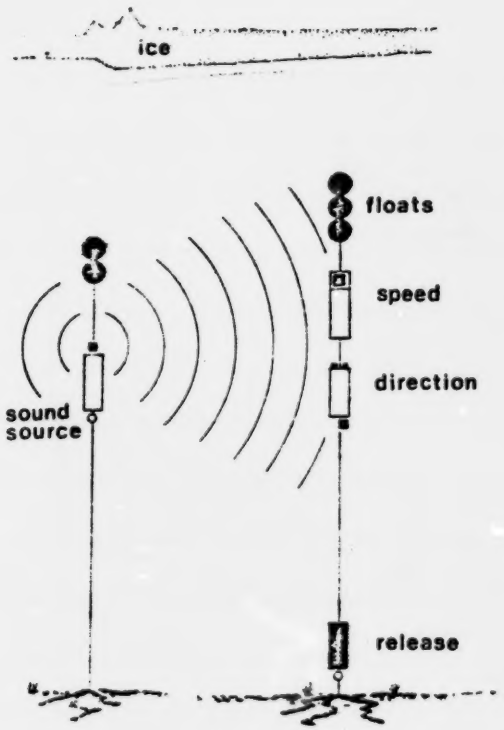
The threat moving sea ice presents to instruments moored in the surface water (0 ∿ 20 m) has been discussed above. The beginning of the period for current measurement below landfast ice is defined by the earliest time one can safely work from the ice. The constraints of adequate ice thickness and sufficient visibility normally preclude periods before mid-February. The cessation of data collection by moored surface instruments is dictated by the time when ice melt and ice motion become a threat. While ice melt occurs in late June - early July, ice motion can be very regional and it is necessary to deal with specific locations on a year to year basis. As an example, Barrow Strait may be covered by fast ice or have extensive areas of open water or moving ice during the entire winter-spring period. Satellite imagery of ice cover in eastern Parry Channel is described by Marko (1978).

The measurement of surface currents in open water was discussed under wind driven currents. This technique provides useful data until freezeup, say in October. The collection of surface current data in the approximate period October to January has never been attempted in the Parry Channel.

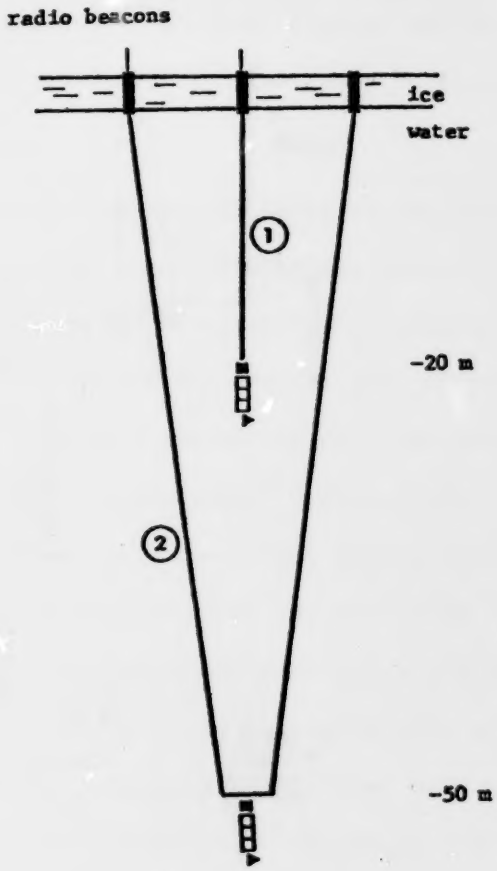
The proximity of Parry Channel to the North Magnetic Pole precludes using conventional current meters to obtain current direction. The techniques used to measure surface currents include suspending the current meter from the ice with a torsionally rigid mooring in the form of a pole or hydraulic hose. The direction of currents to 100 metres has been successfully accomplished by hanging the meter from the ice by means of a bifilar suspension. Both these techniques require the presence of a stable ice cover. Success in obtaining current direction from bottom founded current meters has been limited to locating instruments a few metres off the sea floor. In this case recording current meters were fixed to a tripod which was lowered to the bottom where

its direction was ascertained by means of a gyroscopic compass which served as a short term memory while the compass was returned to the surface. Two innovative methods are being actively developed to obtain current direction at mid-depths for periods of up to one year. One of these is the Sound Oriented Current Meter (SOCM) system which utilizes a sound source moored adjacent to the current meter array as a direction reference. A test of a moored current meter array is scheduled for Wellington Channel in April-May 1981. The disadvantage of the SOCM method is the increase in the cost of instrumentation. A more detailed description of the various schemes above will be found in a paper by Lewis (1980). A second method of obtaining current direction at mid-depths from bottom founded arrays utilizes an "inverted" bifilar suspension which is fixed to the sea floor rather than the ice sheet. Clearly this is a more difficult task to successfully deploy. This system will be tested and, if succesful, deployed in 170 metres of water in Barrow Strait by CCIW in spring, 1981. These systems are illustrated in Figure 14.

The doppler and doppler correlation current meters have been discussed in section 4.2.1. To reiterate, this instrument, when located on the sea floor, has the potential to obtain current profiles on a year-round basis. A prototype suitable for arctic use is not available and an additional effort would be required to accelerate the present program of electronic packaging, software and development and testing.



Sound Oriented Current Meter



Ice Founded Current Meters

1 - hydraulic hose or pole.

2 - bifilar suspension.

Figure 14. Current measurement systems, (after Lewis, 1980).

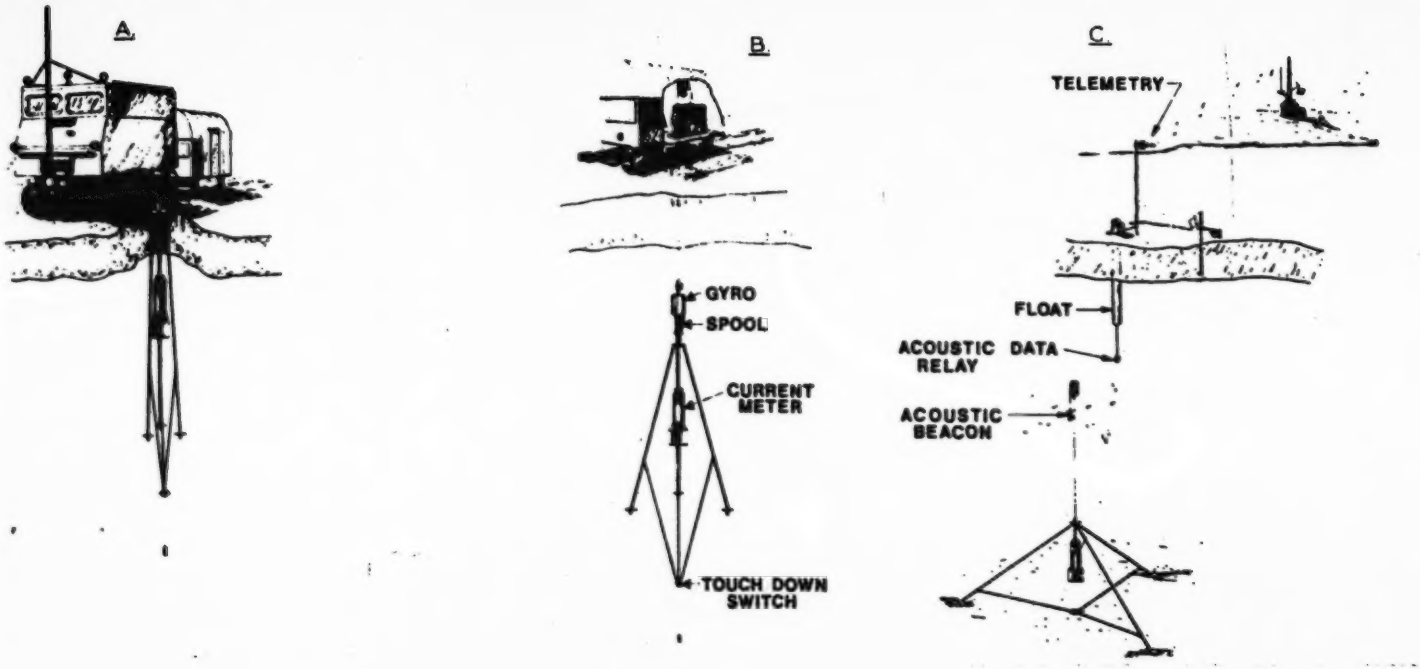


Figure 14. cont'd. Deployment of bottom current measurement system.

8. The Oceanography at Ice Edges

The location of ice edges in the vicinity of the N.W. Passage was discussed under the background review of Section 2 and is illustrated in Figure 2.

The wide variation in edge positions and breakup patterns is not well undersood and the least known aspect is how the ocean affects the advance or retreat of seasonal ice. Relatively warm water associated with oceanic fronts has been found to coincide with ice edges in the Chukchi Sea, (Paquette and Bourke, 1976) and horizontal density gradients associated with the front can give rise to strong local currents. In a review paper, McPhee (1980) discusses the Chukchi Sea data which he shows to be consistent with a complex circulation at the ice margin with a surface current along one direction, a compensating jet at depth farther out and upwelling between them. A schematic of possible geostrophically balanced currents from baroclinic gradients is reproduced from McPhee's paper as Figure 15a. Barber (1977) showed that warm water intrusions from Baffin Bay into Lancaster Sound do occur during winter. These and similar occurrences elsewhere may be a factor in fixing the ice edge in Lancaster Sound, M'Clure Strait and Amundsen Gulf.

McPhee (op. cit.) also discusses a potential circulation due to large gradients in buoyancy flux in both the ocean and atmosphere. Cold air moving from fast ice to water encounters a warmer surface temperature causing the air to become buoyant and establish a seabreeze type circulation. Heat given up to the air results in formation of new ice with an accompanying salt flux into the water column. This flux drives a circulation which is the counterpart of the sea-breeze as illustrated in Figure 15b. As the ice sheet advances in this way the changes in sensible and latent heat flux and salt flux across the ice margin can be large compared to those that might otherwise exist.

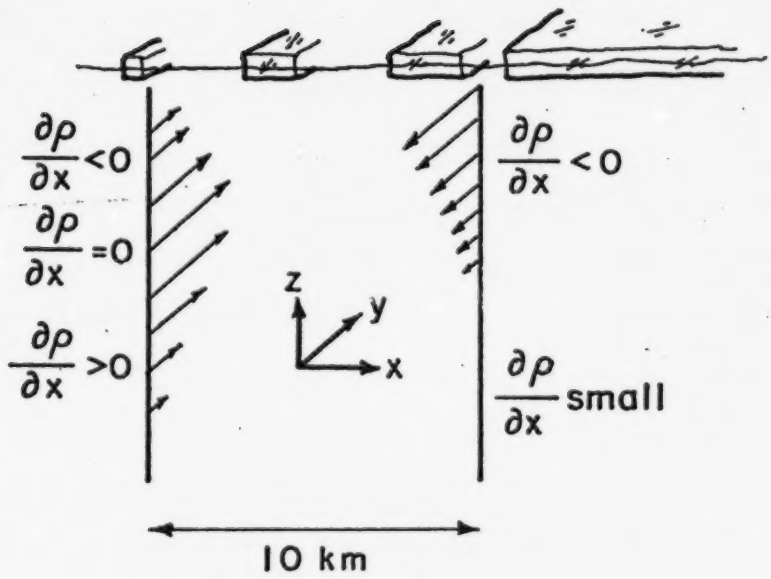


Figure 15a. Schematic of possible geostrophically balanced currents from baroclinic gradients, (after McPhee, 1980).

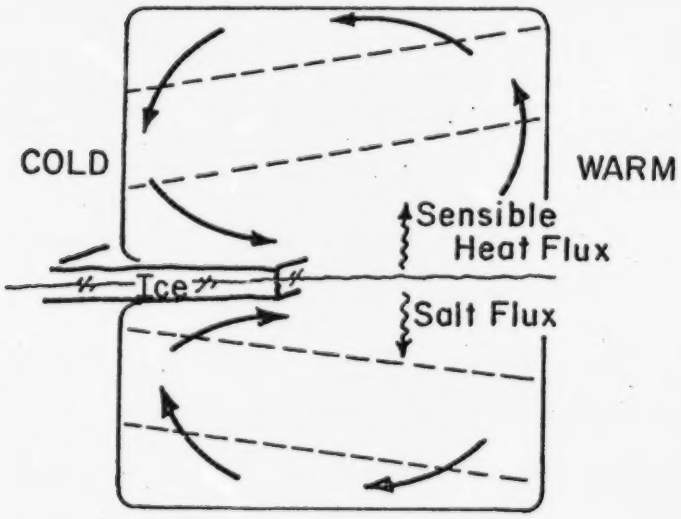


Figure 15b. Schematic of complementary "sea breeze" cells at ice edge when large temperature gradients exist, (after McPhee, 1980).

Wind flowing on to or off an ice sheet can also cause upwelling and "long-shore" currents in a manner similar, though differing in detail, to that which occurs where wind blows on or off land.

The seasonal sea ice zone including conditions at ice edges is receiving increased attention by investigators. Some measurements obtained at ice edges in the N.W. Passage during key periods could assist in understanding the location of ice edges and may be necessary to explain complicated drift buoy tracks.

9. Numerical Modelling

The use of numerical modelling has been discussed in connection with the measurement of water levels (3.3). In general numerical modelling is an aid which can increase the efficiency of field measurements by optimizing the deployment of instruments and as an aid in interpreting data obtained. Numerical models also provide a means to test the reaction of an oceanographic system to various forces such as storm surges, wind, density distribution, etc. Such models are also a predictive tool.

The Arctic Archipelago is an especially favourable application for models, since in theory at least, tidal observations at relatively few boundary locations, where major channels meet the Arctic Ocean or Baffin Bay, should permit satisfactory modelling of tidal heights and currents throughout the system. In practice, some observations are required in the interior of the archipelago in order to optimize parameters and verify model performance.

The current state of modelling technology is such that two-dimensional barotropic models of the whole archipelago are almost certainly feasible. In these, vertical variations in the water column are ignored and only the surface elevation and vertically averaged velocity (or alternatively, mean transport) are computed. Baroclinic models, which include vertical variations in density, velocity, etc., are an order of magnitude more complex and require much more dense networks of initial and boundary observations for successful operation. The computational capacity and costs required are also much higher.

The Numerical Modelling Section at the Institute of Ocean Sciences (I.O.S.) has already developed barotropic models of separate parts of Parry Channel. These were used for computation of wind-driven circulation in Lancaster Sound and tidal propagation studies in M'Clure Strait, but could be rearranged and combined to make a model covering the whole

of Parry Channel. I.O.S. has developed software which at present permits very rapid construction and modification of linear models and work is currently in progress on extending this package to include nonlinear models.

Enough data is available to develop a tidal model of Parry Channel which would give tidal elevations and currents as functions of time all along the Channel. With some further current measurements, the same model could be used to study tidally driven residual barotropic circulation and, with suitable meteorological input, to predict pressure and wind stress effects such as storm surges. All these barotropic phenomena are either of direct interest in themselves or must be quantified before accurate information about either phenomena can be extracted from oceanographic records.

A very useful mode of operation of linear models, which has been explored at I.O.S., is a superposition method which gives a best, physically plausible, least squares fit to available observations in the region modelled even when little is known about conditions at the open boundaries. It would be worthwhile to extend this method to make use of data of mixed type, e.g. to make simultaneous use of surface elevation and current meter data, as it would allow useful deductions to be drawn from observations collected on otherwise uncoordinated field programs. Such a model would be rerun to incorporate additional data as it becomes available.

Given a working barotropic model, it may be worthwhile subsequently to develop a low-cost baroclinic model of Parry Channel using a promising innovative technique currently being developed at I.O.S. for the Strait of Georgia. By using the results of the barotropic model, a time-dependent flexible 'lid' can be defined for a baroclinic model. This permits use of much longer time steps than are customarily possible, thus reducing the computing costs of a baroclinic model to within reasonable limits. A quite extensive field program to provide

initialization and verification data is a prerequisite in this case.

The only arctic models currently under development at I.O.S. are a circulation model of Bridport Inlet and tidal model of M'Clure Strait. Earlier modelling projects in Parry Channel, mostly financed by Petro-Canada, were discontinued as the specific applications were accomplished. However the techniques mentioned above all are in use in models of other areas.

At present, I.O.S. interest in numerical modelling is focussed on the West Coast and the N.E. Pacific. The internal needs of the Department (of Fisheres and Oceans) do not suggest there will be any diversion of effort to arctic models for some time. Nevertheless, the groundwork for a barotropic model of Parry Channel has been done and the project could be revived quickly given modest support.

10. Field Program Proposal.

The area encompassed by the Northwest Passage is immense. The distance from Dundas Peninsula in the west to Brodeur Peninsula in the east is near 1000 km while Parry Channel at its widest exceeds 200 km. To this must be added the 250 km long Prince of Wales Strait. Ten major channels varying in width from 10 to 100 km interact oceanographically with Parry Channel. Measurements on the scale suggested in the preceding discussion, including areas beyond those measured out above, argue that detailed study of the whole passage simultaneously is not practical. The question becomes one of looking at more manageable problems in smaller geographical areas. While studies in limited sectors might be carried out it is essential to not consider a sector in isolation, continuity between areas should exist to provide an understanding of oceanographic features of the N.W. Passage as a whole. For example, a detailed study of a portion of the passage could be undertaken in one year while simultaneously obtaining selected information from the whole Passage. Current, water level, atmospheric and water property data would be obtained at appropriate spatial and temporal scales from within a specified area while in addition, long term current monitoring, regional (i.e. Archipelago wide) water properties, meteorological and water level data would be collected.

The proposals which follow assume that it is important to have some substantial results in hand by 1984 and that it is unlikely that a major spring field effort, involving all participants, could be underway before 1982 which means two spring field efforts (1982 and 1983) could be undertaken. In addition it is possible to have three summer (open water) study periods, 1981-1983. The availability of two seasons for ice founded or spring work suggests dividing the N.W. Passage into two sections which would receive detailed study in subsequent years. Again such studies would be coincident with additional measurements in the larger region and it is realized that

some follow up work may be desirable after the initial detailed study. The geometry of the passage would argue that these would be comprised of an eastern and a western sector. A variety of arguments could be presented as to which sector should be done in the first season and where the division between the sectors should be. As most of the passage is affected by water masses moving from west to east it would be reasonable to gain more detailed understanding of the western sector before turning to the eastern portion. If this argument is adhered to the western sector would be studied in 1982, with the eastern sector following in 1983. The boundary between the sectors is determined by the design of specific programs and the resources available.

Loss of moored instruments in the arctic marine environment is a familiar problem to arctic oceanographers. The resulting loss is two-fold, valuable and often key data is lost and replacement of lost equipment is expensive.

Polar Shelf (EM&R) provides major logistic support primarily to federal government agencies and university groups working in the Canadian Arctic. Those agencies involved in the Northwest Passage program will continue to look to Polar Shelf for logistic support which includes the provision of charter aircraft. The size of this program in 1982-83, which involves several groups operating simultaneously, may tax Polar Shelf's resources and it is to be expected that some additional logistic support will have to be provided by other agencies. For example, a couple of field parties might operate out of Rae Point, using aircraft chartered for their use.

Within the outline of the various projects references are given to preceding sections by number where an expanded general discussion of the topic can be found. The following outlines are only a very brief statement of goals and the methods that might be used to achieve these goals. Where appropriate related studies are indicated and an indication of the instruments

required is given. The term "responsible agency" in some cases indicates an existing committment but in most cases should be regarded as tentative and subject to discussion. Clearly a large amount of scientific planning will have to go into those projects not presently underway.

The following abbreviations are used in the outlines which follow:

DFO - Department of Fisheries and Oceans, Ocean Science and Surveys Branch.

CCIW - Canadian Centre for Inland Waters, Burlington, Ontario.

IOS - Institute of Ocean Sciences, Sidney, B.C.

CHS - Canadian Hydrographic Service

AES - Atmospheric Environment Service, Dept. of the Environment.

WLR - water level recorder or tide gauge

RCM - recording current meter

CTD - conductivity-temperature-depth instrument.

10.1 Program Proposal - 1981

The 1981 program proposal is really a statement of work presently planned and underway or being actively considered for the 1981 field season.

The Ocean Information Division at IOS with support from industry is supporting a number of contracts which will bring together all available oceanographic data from industrial and government sources. This work will evaluate the existing data and, where warranted, put together a regional picture. Work on the Beaufort Sea data is underway with work in the Sverdrup Basin started. The Northwest Passage area will then be done with all work completed by Fall, 1981.

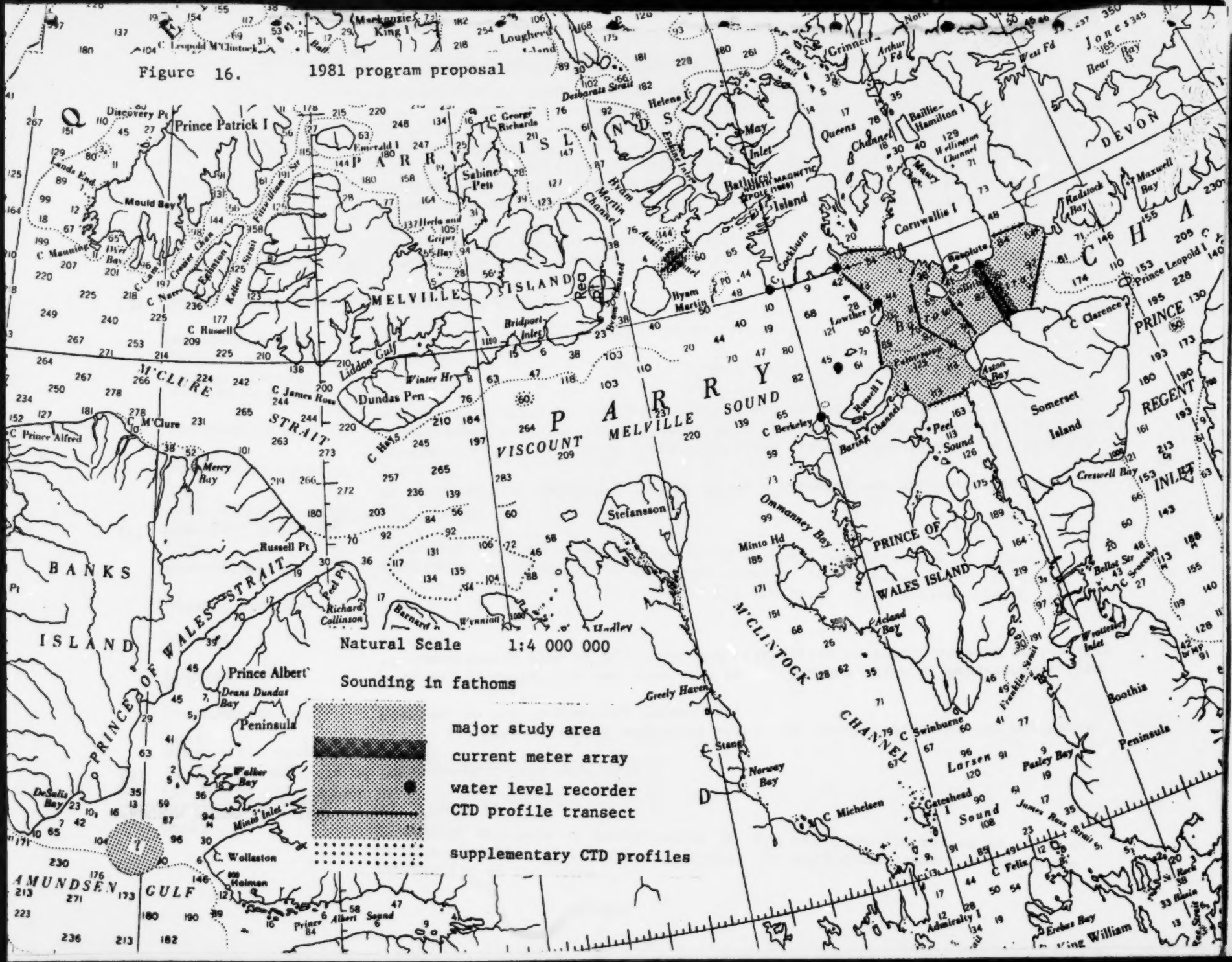
The Numerical Modelling Group at IOS plans to develop barotropic models of the M 'Clure Strait - Viscount Melville Sound area.

During 1981 CCIW will begin a multiyear study in Barrow Strait which will look at seasonal and inter-annual variations in flow, estimate net transport and identify currents and establish their type and origin.

McGill University is carrying out a program of current and water structure measurements in Austin Channel.

Monitoring of ice movement and surface currents could occur in the summer period.

Figure 16. 1981 program proposal



PROGRAM PROPOSAL - 1981 ref. Figure 16.

(1) Review and Analysis of Oceanographic Data Available

Goal: Review all data presently available within the general area of the Northwest Passage, to aid in planning future work.

Method: Compile available data and summarize as to location, time of measurement, type of measurement, type of equipment and calibration thereof; estimate reliability of data.

Related Studies:

Responsible Agency: DFO-IOS. A. Cornford - I.O.S.

(2) Numerical Modelling

Goal: To use numerical modelling techniques as a planning and interpretive aid.

Method: Develop a tidal model of M'Clure Strait and Viscount Melville Sound. Develop a barotropic model of Parry Channel as a linear model for optimum interpolation and interpretation of available current and surface elevation data, ref. 9.

Related Studies:

Responsible Agency: DFO-IOS, Industry contract.

(3) Oceanographic Processes - Barrow Strait

Goal: Identify currents, their type and origin; determine seasonal and inter-annual variations in flow and transport estimates.

Method: Commence three year long program of measurements in Barrow Strait. Measure currents across the strait with some measurements to be year round, ref. 4.1, 4.2, 4.3. Measure tides in region and use water level measurements to obtain year-long estimates of net surface transport, ref. 3.1, 4.2. Measure water properties across strait plus several transects to the west and east, ref. 6, 4.3. Gather data on variations of current and water properties with depth over a tidal cycle. Gather data on chemical tracers.

Related Studies: see following years

Instrumentation: ~ 11 WLR, 15 RCM, CTD

Responsible Agency: DFO-CCIW, CHS

(4) Oceanographic Processes - Austin Channel

Goal: (Details of this work were not available at the time of writing; the program is included here for the sake of completeness.

Method: (Involves current measurements at one location for 30 days and CTD transect).

Related Studies:

Instrumentation: 2 RCM, CTD

Responsible Agency: McGill

(5) Long Term Mean Water Level Changes

Goal: Determine suitable sites for recording seasonal and inter-annual changes in mean water level along the northwest coast of the Archipelago on the Arctic Ocean and in Baffin Bay in order to illuminate changes in flow through the Archipelago, ref. 4.2.

Method:

Related Studies: See following years.

Instrumentation:

Responsible Agency: DFO-CHS

(6) Ice Motion and Surface Currents During Summer

Goal: To monitor and gain an understanding of open water and ice motion in response to oceanographic and atmospheric forces. To understand ocean-ice-atmosphere interaction at ice edges.

Method: Use drift buoys as Lagrangian tracers of ice and surface currents. In addition use remote sensing techniques such as radar and satellite imagery. A meteorological and water level network is required to obtain information on atmospheric forcing, ref. 4.4. Ice edge studies would require water structure measurements in the vicinity of an ice edge, ref. 8.

Related Studies: see following years

Instrumentation: Satellite or HF radar tracked buoys, SHF and/or HF radar.

Responsible Agency:

(7) Sea Ice

Goal: Document sea ice distribution, morphology, thickness and relate to oceanographic, meteorological and historical factors.

Method: Aerial surveillance using visual, photographic, SLAR or other remote sensing techniques with ground (ice) founded survey using ice coring, impulse radar or other available techniques.

Related Studies: see following years

Instrumentation:

Responsible Agency: Industrial contract;
A.E.S. - Ice Central (?)
C.C.R.S. (?)
McGill (?)

10.2 Program Proposal - 1982

The 1982 program concentrates on the western sector of the Northwest Passage. This area includes Prince of Wales Strait and the area bounded by M'Clure Strait in the west and tentatively a line north of Stefansson Island in the east. A spring program working off the ice in this area would study channel flow in Prince of Wales Strait, an area which may be well suited for this study. In addition a description of the oceanographic processes in western Viscount Melville Sound and Prince of Wales Strait with measurements aimed at understanding the spatial and temporal variations found would be undertaken. The program would include water level, current and water structure measurement. The program of current variability and water structure measurement in Barrow Strait would continue from the previous year. A regional survey of water structure in the Archipelago would support both the above programs.

Permanent monitoring of water levels along the north-west coast of the archipelago and in Baffin Bay will be initiated to provide a record of seasonal and interannual variations as an essential component in understanding seasonal variations in water flow.

Numerical models developed to date would be run using data available from the 1981 and spring 1982. The models would serve as a project planning aid and would also function as an interpretive tool.

The monitoring of ice movement and surface currents would occur during the summer period. Drift buoys would function as Lagrangian tracers to determine ice and water movement. This effort could be augmented by radar tracking. Water level recorders will record changes in response to wind stress and atmospheric conditions would be monitored using a system of atmospheric pressure gauges and anemometers.

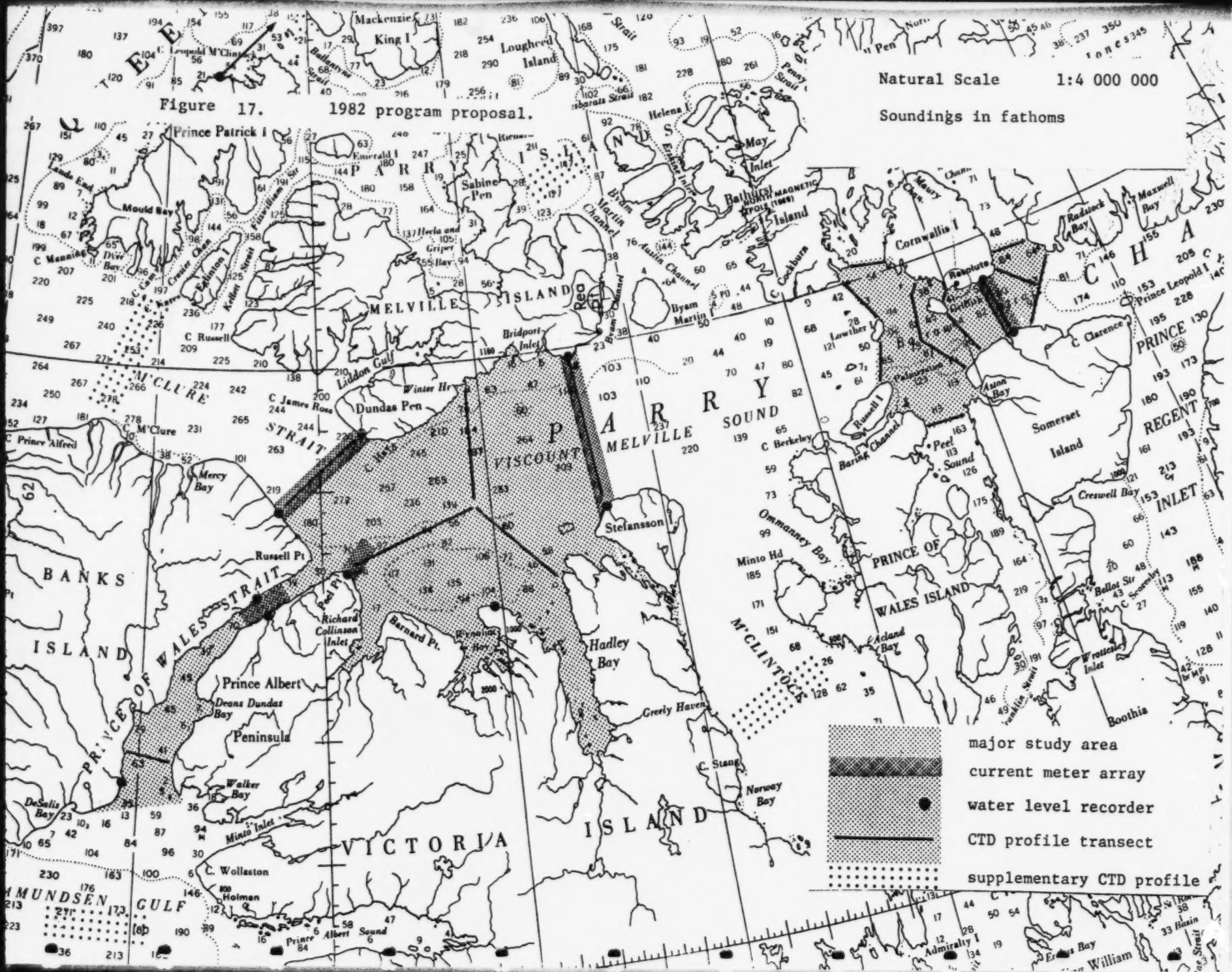


Figure 17. 1982 program proposal.

PROGRAM PROPOSAL - 1982 ref. Figure 17

(1) Numerical Modelling

Goal: To use numerical modelling techniques as a planning and interpretive aid.

Method: Run linear barotropic model of Parry Channel using 1981, 1982 data. Develop and run nonlinear model for tidal, tidally-driven circulation and meteorologically driven surge and circulation studies. Ref. 9.

Related Studies: (3, 4, 5, 6, 7)

Responsible Agency: DFO-IOS F. Henry, Numerical Modelling Group.
Possible assistance from Dome Petroleum.

(2) Channel Flow

Goal: To evaluate the technique of using the measurement of sea surface slope to determine surface transport on a year round basis.

Method: Deploy water level gauges for a one year period on opposite sides of Prince of Wales Strait. Use a number of surface current meters to form a cross-channel transect to calibrate water level gauges for a period of one month. Ref. 4.2.

Related Studies: results influence use of same technique in other channels, see (3, 4, 6) and following year.

Instrumentation: 4 WLR, 10 RCM

Responsible Agency: DFO - IOS; DFO-CHS H. Melling - Frozen Sea Research Group. I.O.S.

(3) Oceanographic Processes - Western N.W. Passage

Goal: To obtain a description of oceanographic processes in western Viscount Melville Sound and Prince of Wales Strait with emphasis on winter conditions; to determine which processes are important; to determine spatial and temporal variations; to determine circulation patterns, transport and origin of water masses.

Method: Measure tides along north and south shores of V. Mel. Sd., ref. 3.1. Determine

Method: (cont'd) tidal currents across M'Clure Str., north of Stephansson Island, in Prince of Wales Strait, and V. Mel. Sound adjacent to Pr. Wales Str., ref. 4.1, 4.2. Measure water properties in western V. Mel. Sd. and Pr. Wales Str. with series of CTD transects, measure variability using CT chains, ref. 6. Measure flow associated with baroclinic currents and transport, ref. 3.2, 4.3, estimate temporal variability of net surface flow with water level gauges across M'Clure Str. and north of Stefansson Isld., ref. 4.2. Some water level and current measurements should span a minimum of one year.

Related Studies: (1, 2, 4, 5, 6) and following year.

Instrumentation: ≃ 8 WLR, ≃ 30 RCM, CTD, ≃ 5 CT chains

Responsible Agency: DFO-IOS DFO-CHS R. Lake - Frozen Sea Research Group - I.O.S.
Industry Contract. F. Stephensen, CHS, I.O.S.
D. St. Jacques - CHS, CCIW

(4) Oceanographic Processes - Barrow Strait.

Goal: Identify currents, their type and origin; determine seasonal and inter-annual variations in flow and transport estimates.

Method: Measure currents across Strait with some year-round measurements, ref. 4.1, 4.2, 4.3. Measure tides in region and use water level measurements to obtain year long estimate of surface transport, ref. 3.1, 4.2. Measure water properties across Strait plus several transects to the west and east, ref. 6, 4.3. Gather data on chemical tracers. Vertical profiles of current and water properties over tidal cycle.

Related Studies: (1, 2, 3, 5, 6) and preceeding and following year.

Instrumentation: 4 WLR, 18 RCM, CTD.

Responsible Agency: DFO-CCIW, DFO-CHS S. Prinsenberg - CCIW
D. St. Jacques - CHS, CCIW

(5) Regional Water Structure

Goal: Identify characteristics of main water masses to assist in understanding interaction of water in and adjacent to the Northwest Passage.

Method: Conduct an airborne CTD survey in Amundsen Gulf, western M 'Clure Strait, Sverdrup Basin, Lancaster Sound, Gulf of Boothia (?) and M'Clintock Channel, ref. 6.

Related Studies: 3, 4, and following year.

Instrumentation: CTD

Responsible Agency: DFO-IOS Work to be one by contract with possible industrial assistance

(6) Long Term Mean Water Level Changes

Goal: Determine seasonal and inter-annual changes in mean water level along the northwest coast of the archipelago on the Arctic Ocean and in Baffin Bay in order to illuminate changes in flow through the Archipelago. Ref. 4.2.

Method: Establish year round monitoring of water levels.

Related Studies: 3, 4, and following year.

Instrumentation: ~ 4 WLR

Responsible Agency: DFO-CHS. F. Stephensen, CHS - I.O.S.

(7) Ice Motion and Surface Currents During Summer

Goal: To monitor and gain an understanding of open water and ice motion in response to oceanographic and atmospheric forces. To understand ocean-ice-atmosphere interaction at ice edges.

Method: Use drift buoys as Lagrangian tracers of ice and surface currents. In addition use remote sensing techniques such as radar and satellite imagery. A meteorological and water level network is required to obtain information on atmospheric forcing, ref. 4.4. Ice edge studies would require water structure measurements in the vicinity of an ice edge, ref. 8.

Related Studies: see preceding and following years.

Instrumentation: Satellite or HF radar tracked buoys. SHF and/or HF radar.

Responsible Agency: Possible industrial contract.

(8) Sea Ice

Goal: Document sea ice distribution, morphology, thickness and relate to oceanographic, meteorological and historical factors.

Method: Aerial surveillance using visual, photographic SLAR or other remote sensing techniques with ground (ice) founded survey using ice coring, impulse radar or other available techniques.

Related Studies:

Instrumentation:

Responsible Agency: Industrial contract; A.E.S.-Ice Central(?), McGill (?), CCRS (?).

10.3 Program Proposal - 1983.

The 1983 program concentrates on the eastern sector of the Northwest Passage. The area would be bounded in the west by a tentative line north of Stefansson Island, thus providing some continuity with the previous years' work. In the east the area would be bounded by Barrow Strait where long term measurements would be continuing into the third year. The boundary to the north is across Byam and Austin Channels and McDougal Sound and in the south across the M'Clintock Channel and Peel Sound. Within this area work would be undertaken to describe the oceanographic processes present with water level, current and water structure data being obtained with the goal of understanding the spatial and temporal variations found. As previous oceanographic studies (Greisman and Lake, 1978) have occurred in the channels on the north side of the area some information, e.g. tidal currents, is available so that if resources are sufficiently limited the emphasis should be on M'Clintock Channel and Peel Sound to the south. Transects of CTD profiles would be taken across the various channels together with transects within the sector. A regional survey of water structure in the Archipelago similiar to the previous year would be done.

An oceanographic study of Prince Regent Inlet would also be undertaken with the goal of understanding the physical processes occurring there. Some additional work might be considered in the area north of the inlet in Lancaster Sound and/or in Wellington Channel.

Permanent monitoring of water levels along the north-west coast of the archipelago and in Baffin Bay would continue to provide a year round record of mean water levels. Variations in mean water level are thought to be a possible cause of seasonal changes in mean transport through the archipelago.

Numerical models developed to date would be run using data available

from previous years and spring 1983. Again, models would serve as a project planning aid and would also function as an interpretive tool.

A portion of the field effort and logistic support would be directed toward recovering current meters and water level recorders deployed during the 1982 field season. Some equipment may be redeployed at selected sites within the 1982 study sector to provide a longer term data base or to elucidate some particular aspect of the oceanographic picture.

The monitoring of ice movement and surface currents would again be repeated during the summer period. The techniques and study area would be similiar to or expanded from the 1982 summer program.

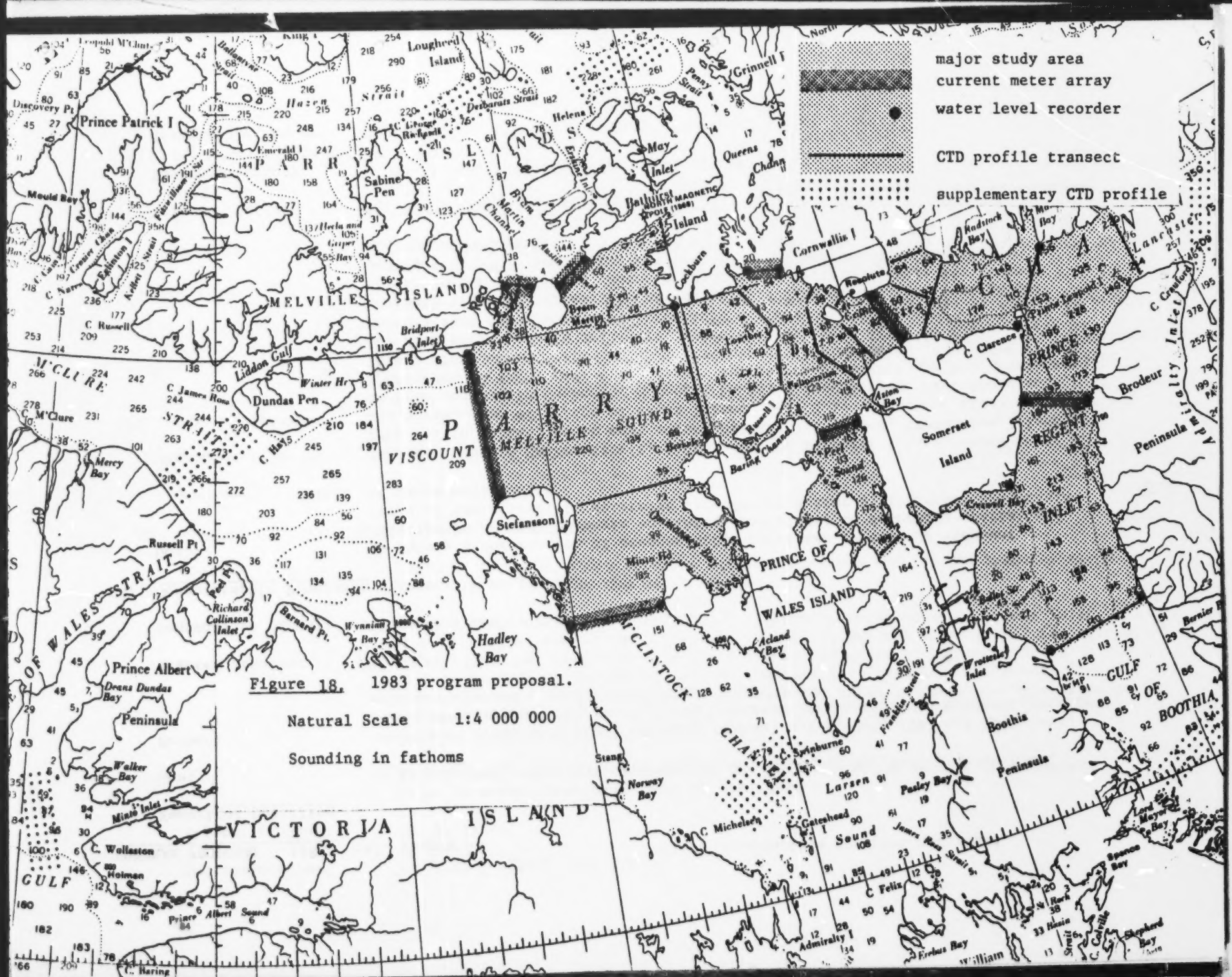


Figure 18. 1983 program proposal.

Natural Scale 1:4 000 000

Sounding in fathoms

PROGRAM PROPOSAL - 1983. ref. Figure 18 Note: Responsible Agencies not fixed.

(1) Numerical Modelling

Goal: To use numerical modelling techniques as a planning and interpretive tool.

Method: Run linear barotropic model of Parry Channel using 1981, 1982 and 1983 data. Run nonlinear model for tidal, tidally-driven circulation and meteorologically driven surge and circulation studies. Ref. 9.

Related Studies: (2, 3, 4, 7)

Responsible Agency: DFO-IOS, Industry contract.

(2) Oceanographic Processes - Eastern N.W. Passage

Goal: To obtain a description of oceanographic processes in eastern Viscount Melville Sound with emphasis on winter conditions; to determine spatial and temporal variations; to determine circulation patterns, transport and origin of water masses.

Method: Measure tides in Barrow Strait, south shore of Bathurst Island, south shore of Byam Martin Island, south east corner of Melville Island, Stefansson Island and the north shore of Prince of Wales Island, ref. 3.1. Determine tidal currents in Byam and Austin Channels, McDougal Sound, Barrow Strait, Peel Sound and M'Clintock Channel, ref. 4.1. Repeat current measurements north of Stefansson Island if required, ref. 10.3(3). Measure water properties in eastern V. Mel. Sd. with series of CTD transects, measure variability using CT chains, ref. 6. Measure flow associated with baroclinic currents and transport, ref 3.2, 4.3; estimate temporal variability of net surface flow with water level gauges across Barrow Strait and channels adjacent to eastern V. Mel. Sd. listed above, ref. 4.2. Some water level and current measurements should span a minimum of one year.

Related Studies: (1, 3, 5, 6) and preceding year.

Instrumentation: $\sim$ 12-15 WLR, $\overset{\sim}{\sim}$ 45 RCM, CTD $\sim$ 5 CT chains

Responsible Agency: DFO-IOS/CCIW, DFO-CHS, Industry contract.

(3) Oceanographic Processes - Barrow Strait

Goal: Identify currents, their type and origin; determine seasonal and inter-annual variations in flow and transport estimates.

Method: In 1983 this study, continuing from previous years, becomes integrated into the study of eastern Viscount Melville Sound (see preceding project).

Measure currents across strait with some year round measurements, ref. 4.1, 4.2, 4.3. Measure tides in region and use water level measurements to obtain year long estimates of surface transport, ref. 3.1, 4.2. Measure water properties across strait plus several transects to the west and east, ref. 6, 4.3. Gather data on chemical tracers.

Related Studies: (1, 2, 5, 6) and

Instrumentation: 4 WLR, 18 RCM, CTD.

Responsible Agency: DFO-CCIW, DFO-CHS

(4) Oceanographic Processes - Prince Regent Inlet

Goal: Identify currents, their type and origin; determine spatial and temporal variations in flow patterns and water masses.

Method: Measure tides along Inlet, ref. 3.1. Determine tidal currents across Inlet from the ice at one or two transects, ref. 4.1. Measure water properties across Inlet in several transects from the north end adjacent to Lancaster Sound to the Gulf of Boothia in the south, ref. 6. Measure flow associated with baroclinic currents and transport, Ref. 4.3., 6. Possibly estimate temporal variability of net surface flow with water level measurements on opposite sides of the channel over a period of a year, ref. 3.1, 4.2.

Measurements requiring landfast ice may be difficult as ice in Prince Regent Inlet is moving throughout much of the year.

Related Studies: (1, 5, 6)

Instrumentation: $\simeq$ 6 WLR, $\simeq$ 18-20 RCM, CTD

Responsible Agency: DFO- , Industry contract.

(5) Regional Water Structure

Goal: Identify characteristics of main water masses to assist in understanding interaction of water within and adjacent to the Northwest Passage. Identify inter-annual changes.

Method: Conduct an airborne CTD survey in Amundsen Gulf, McClure Strait, Sverdrup Basin, Lancaster Sound, Gulf of Boothia, M'Clintock Channel and Peel Sound. Several measurements would duplicate those taken during the previous year, ref. 6.

Related Studies: (2, 3, 4)

Instrumentation: CTD

Responsible Agency: DFO-IOS

(6) Long Term Mean WAter Level Changes

Goal: Determine seasonal and inter-annual changes in mean water level along the northwest coast of the Archipelago on the Arctic Ocean and in Baffin Bay in order to illuminate changes in flow through the Archipelago.

Method: Continue year round monitoring of water levels.

Related Studies: (2, 3, 4,) and preceding years.

Instrumentation: 4 WLR

Responsible Agency: DFO-CHS

(7) Ice Motion and Surface Currents During Summer

Goal: To monitor and gain an understanding of open water and ice motion in response to oceanographic and atmospheric forces. To understand ocean/ice/atmosphere interaction at ice edges.

Method: Use drift buoys as Lagrangian tracers of ice and surface currents. In addition

use remote sensing techniques such as radar and satellite imagery. A meteorological and water level network is required to obtain information on atmospheric forcing ref. 4.4. Ice edge studies would require water structure measurements in the vicinity of an ice edge, ref. 8.

Related Studies: See preceding years.

Instrumentation: Satellite or HF radar tracked buoys. SHF and/or HF radar.

Responsible Agency:

(8) Sea Ice

Goal: Document sea ice distribution, morphology, thickness and relate to oceanographic, meteorological and historical factors.

Method: Aerial surveillance using visual, photographic, SLAR or other remote sensing techniques with ground (ice) founded survey using ice coring, impulse radar or other available techniques.

Related Studies: see preceding years.

Instrumentation:

Responsible Agency: Industrial contract; A.E.S. - Ice Central (?), McGill (?), C.C.R.S. (?).

10.4 Program Proposal - 1984

The emphasis in 1984 field effort would be the recovery of instruments deployed during the previous year.

Numerical models developed during the previous few years would be run using the complete data sets.

Continuing analysis and interpretation of data would occur. The work should be concluded with a regional report dealing with Northwest Passage Oceanography as a whole.

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